Conference Paper

On Mineral Resources for Ferroalloy Production

Grigory A. Mashkovtsev and Tatiana V. Bakanova

N. M. Fedorovsky All-Russian Research Institute of Mineral Raw Materials, Moscow, Russia

Abstract

The article addresses the issues associated with self-sufficiency of raw materials in the Russian ferroalloy industry. The analysis of characteristic features of the domestic ferroalloy mineral resource base is done. Prospective technology solutions developed by the VIMS Federal State Budget Institution to be used for the industrial processing of low-grade and difficult ores are presented. A comprehensive approach to resolve resource self-sufficiency issues for the domestic ferroalloy industry is outlined, based on the development and implementation of highly efficient ore-processing technologies and on geology exploration for new ore resources that could be developed in both process- and cost-efficient ways.

Keywords: ferroalloys, mineral resources, production, consumption, deposits, reserves, technologies

Corresponding Author:
Grigory A. Mashkovtsev
vims@df.ru

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1. Introduction

Currently, over 100 sorts of ferroalloys are produced in Russia with the annual output totaling over 2 million tons and the specific ferroalloy consumption standing at some 30 kg per ton of steel on the average. Both the output and the consumption of ferroalloys are set to rise due to ongoing increase in the demand for quality grades of steel.

The largest output and consumption ferroalloys are ferrosilicon (50% of the ferroalloy output/consumption total), ferromanganese and ferrosilicon manganese (25%), ferrochrome and ferrosilicon chrome (17%). The scope of summary production/consumption of the above accounts for over 90% of the entire production and consumption volume of all ferroalloys produced. Ferroalloys of titanium, niobium, molybdenum, tungsten, vanadium, nickel etc. are produced and consumed on considerably lesser scale compared to the above ferroalloy types. The focus of this article will be on mineral resource supply for the production of the most-demanded ferroalloys.

Ferrosilicon is used as an alloy additive essential for the production of high-elasticity grades of steel used for the production of technical springs and shock absorbers, and also for steel for construction and instrumental applications. It steadily holds the leading place in the Russian ferroalloy industry as the main product for both the domestic consumption and the export. The overall production of ferrosilicon in Russia totaled 543 000 tons in 2017, the main producers being the ferroalloy plants situated in Bratsk, Serov, Novokuznetsk and Chelyabinsk. The apparent domestic consumption of ferrosilicon in Russia in 2017 stood at ca. 240 000 tons, with the surplus product exported to Japan, the Netherlands, South Korea and other non-CIS countries (see Figure 1). Russia has an extensive resource base of both quartzites and iron ores needed to produce ferrosilicon, yet far from all of the domestic quartzite deposits can yield high-grade concentrate containing 99.9% silicon dioxide and above, which is essential for the quality ferrosilicon production.

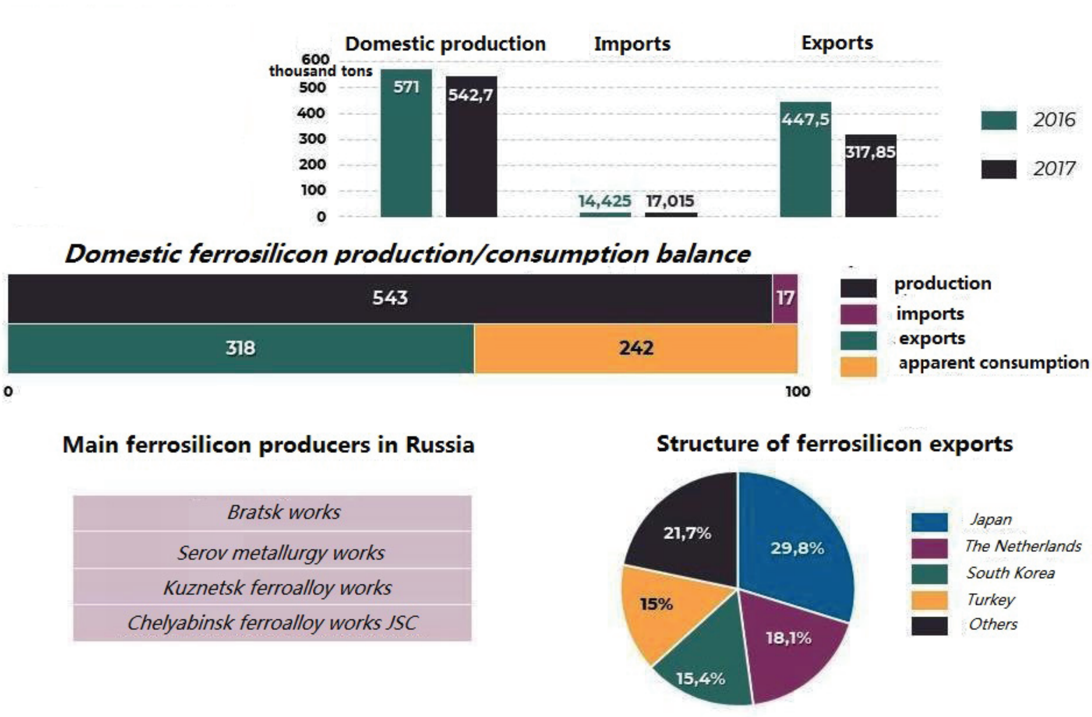

Figure 1: Ferrosilicon production and consumption.

Manganese-based ferroalloys are highly prominent ones in the large-volume bulk produced ferroalloys group when it comes to both the production and consumption amounts. In 2017, ferromanganese production in Russia increased about 25% on 2016 while the ferrosilicon manganese output rose 29.5% on the preceding year, bringing up the overall manganese-based ferroalloys production to 463 000 tons. However, 190 000 tons of ferromanganese and ferrosilicon manganese is still imported to fully meet the domestic demand for these ferroalloys estimated at some 580 000 tons (see Figure 2).

It is noted that while the domestic consumption of manganese-based ferroalloys is quite considerable, practically no mining of manganese ores is done in Russia at present,

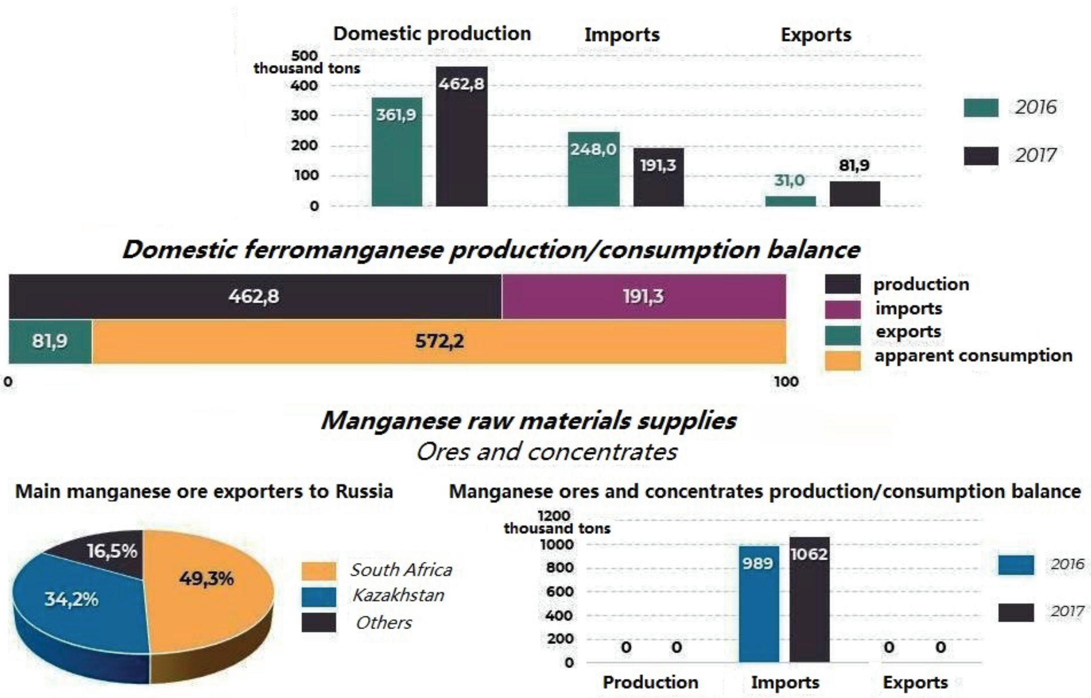

Figure 2: Manganese ferroalloys production and consumption.

with all the ores imported from the Republic of South Africa, Kazakhstan and other countries. The cause of such a negative situation is associated with three issues: inferior quality of domestic manganese ores, lack of industrial technologies for the processing of such ores and domestic resource management shortcomings.

The balance reserves of manganese ores in Russia (resource classification categories A, B, C_1 and C_2) total about 230 million tons, the prognosticated resources (resource classification categories P_1 and P_2) – 37 million tons, with category P_3 resources accounting for 615 million tons [1]. The reserves and prognosticated resources of manganese ores in Russia occur in 29 deposits with the ore resources subdivided into three basic geological industrial types: carbonate ores, oxide ores and mixed ores (see Table 1). In addition to these, there exist a large Utkhumskoye silicate-manganese ore occurrence (60 million tons of Mn according to P1 resource classification grade), sulfidic manganese ore occurrences ($C_{Mn} \sim 40\%$) in Republic of Sakha (Yakutia) along with numerous ferromanganese nodule-type oceanic and marine floor-type ore clusters [4]. The bulk of the manganese ore potential of Russia is represented by Usinskoye, Porozhinskoye, Yuzhno-Khinganskoye deposits, by the North Urals ore deposit cluster (Ivdelskoye, Marsyatskoye and other deposits) and also by Parnokskoye deposit. The main problems of those deposits are high carbonate content in the ores of Usinskoye deposit (the biggest manganese deposit in Russia) considerably complicating the ore processing technology, and also low manganese grades characteristically for all these deposits (20

– 25% Mn), except Parnokskoye deposit where the ore grade stands at 30% Mn. Besides, there also exists a set of low-grade (15 – 20% Mn) manganese ore deposits in the south part of Krasnoyarsk Territory which have been explored and estimated, characterized by high phosphorus content (in excess of 0.3% P) making the ores unfit for metallurgy purposes. However, the above problems can be successfully overcome in case modern ore processing technologies are employed.

Table 1: The main manganese ore deposits of Russia.

#	Name and administrative-territorial location	Geological industrial ore type	Reserves (categories ABC_1+C_2), thousand tons Mn	Mn reserves, % of the total	Average ore grade, % Mn
Allocated reserves					
1	Usinskoye (Kemerovo Region)	Carbonate ores	121 685	52,9	19,72
		Oxide ores	6 011	2,6	25,57
2	Yuzhno-Khinganskoye (Jewish Autonomous Region)	Carbonate ores	127	0,06	18,09
		Mixed ores	8 097	3,5	20,88
		Oxide ores	666	0,3	21,09
3	Parnokskoye (Komi Republic)	Carbonate ores	1 007	0,4	30,47
		Oxide ores	1 003	0,4	31,62
Non-allocated reserves					
4	Porozhinskoye (Krasnoyarsk Territory)	Oxide ores	29 463	12,8	18,85

The VIMS Federal State Budget Institution (the VIMS) has conducted the technology assessment of the main geology industrial types of the domestic manganese ores for the processing (See Figure 3).

The processing of the carbonate-type ores is based on the preliminary radiometric enrichment of the ores to produce concentrate with the manganese grade of 35–40% Mn, which, in turn, is to be hydrometallurgically treated to obtain electrolytic metal manganese (EMM) which can be easily converted into ferromanganese.

The processing of mixed silicate-carbonate manganese ores, according to the VIMS, is to be based on a two-stage technology which envisages the melting of manganese-containing slag directly from the ore, which product is to be pyrometallurgically processed next to obtain highly marketable СМн-17 grade silicon manganese.

Laboratory-scale percolation leaching trials performed by the VIMS enabled the successful production of high-grade manganese concentrate (HMC) featuring the grades of about 60% Mn from low-grade manganese ores of the Seiba type. The said HMC cannot

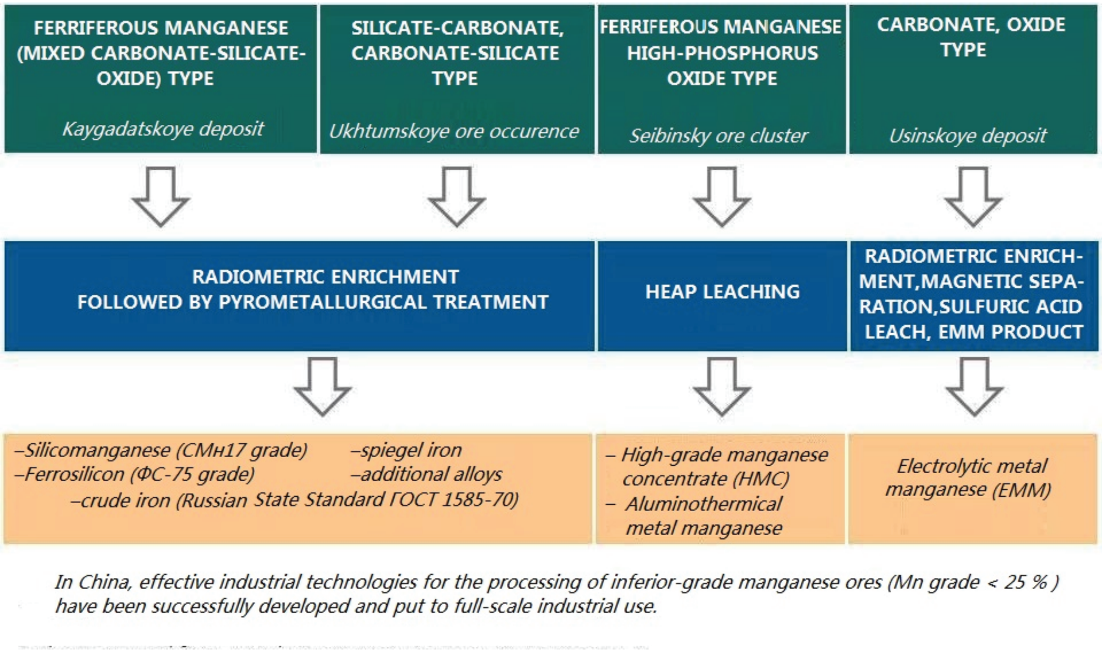

Figure 3: Technologies for manganese ore processing.

be processed into marketable products if the traditional technologies are used because of high phosphorus and arsenic contents in it.

Currently, the VIMS is conducting a bulk heap leach trial involving a 15-ton low-grade oxide ore sample taken from the Kozinskaya manganese ore cluster group (Krasnoyarsk Territory). The anticipated positive outcome of the experiment will pave the way for developing efficient methods of the development of a whole group of resource objects situated in South Siberia and the South Urals.

Among Russia's main manganese ore deposits described above, Usinskoye and Porozhinskoye deposits hold the top priority. Parnokskoye deposit's manganese reserves appear too small (about 2 million tons Mn) while Yuzhno-Khinganskoye deposit is being developed by a Chinese company.

The Usinskoye deposit (Kemerovo Region, with carbonate type ore reserves of 121,6 million tons Mn and oxide type ore reserves of 6 million tons Mn) is in the most advanced pre-development stage. Its design capacity for ore is 700 000 tpa (tons per year), for concentrate – 500 000 tpa, for electrolysis metal manganese, easily convertible into ferroalloys – 80 000 tpa. The proposed technology scheme provides for the production of manganese concentrate containing up to 40% Mn by means of radiometric concentration. The concentrate is to be processed further for electrolysis metal manganese (EMM) at a special plant in the Republic of Khakassia. However, the preparation of the plant for commercial operation, which took the operator company (Chek-SU.VK CJSC) over 10 years to bring to near-completion stage, has been suspended in 2016 following the creditor entities forcing the above company to file for bankruptcy. The resumption of work aimed at launching the entire ore object into commercial operation is highly needed proceeding from the standpoint of both the interests of the state and the metallurgical industry of this country. However, in case the Usinskoye plant is finally brought into operation at full design capacity (400 000 tpa Mn) its output will still be short of the industry's demand (only about 40% of the manganese concentrate needed). For this reason, the timely preparation of Porozhinskoye deposit (reserves totaling 28 million tons in oxide-type ores. the average grade being about 19% Mn) for full-scale commercial development looks like a matter of urgency. In addition, the development and commercialization of minor manganese ore deposits situated in the south parts of Krasnoyarsk Territory and the South Urals looks a highly promising step in the import substitution strategy in the manganese resource field. It is to be emphasized, however, that taking into account low manganese grades and high phosphorus contents in the ores of these deposits the staging of individual heap leach trials is needed to develop the technology regulations for efficient ore processing, taking into account the technology peculiarities of the respective resources.

Along with the implementation of steps aimed at the development and commercialization of the deposits already discovered and assessed, prospecting for new manganese resources is to be continued, proceeding from commercial development efficiency indicators such as the manganese grades of 30% Mn and more. Prerequisites for discovering such resources exist in regions such as the foothill belt of the Polar Urals and the southern part of Siberia, where the prospecting will involve and necessitate the drilling studies of manganiferous ore formations overlain by Neogene-Quaternary deposits.

Ferrochromium is produced in Russia at the Serov, Chelyabinsk and Klyuchevsky ferroalloy works (all situated in the Urals region) and at the Tikhvin works (Leningrad Region). In 2017, the ferrochromium output in Russia totaled 364 000 tons, from which amount 104 000 tons is consumed within Russia while the rest is exported (See Figure 4). However, only 40% of the source ore comes from domestic sources while the rest of the ore (867 000 tons) is imported from Kazakhstan and South Africa. The chief reason of the underuse of the domestic chromium resource base consists of both the low grade of the chromium ores available and the lack of efficient processing technologies for these.

The available resources of chromite in Russia are relatively small, totaling 52 million tons in resource categories A, B, C_1 and C_2, 352 million tons in prognosticated resource categories P_1 and P_2 while another 170 million tons is comprised by the P3 category prognosticated resources. The main chromite ore deposits in Russia are Tsentralnoye and Zapadnoye (Yamal-Nenets Autonomous District), Glavnoye Saranovskoye

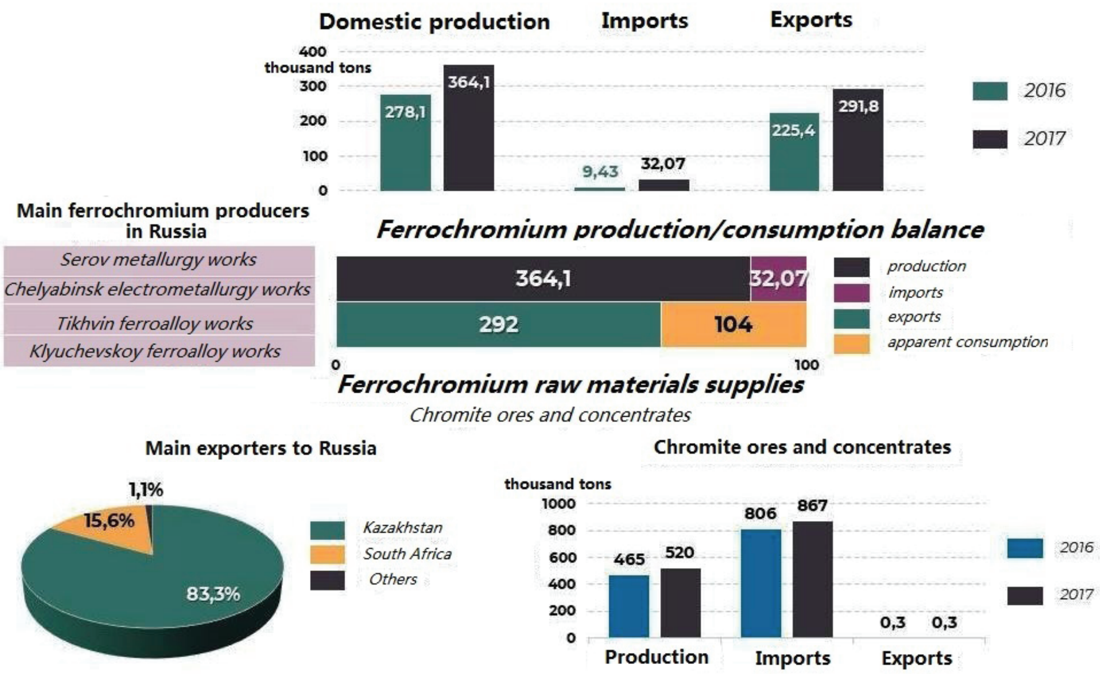

Figure 4: Ferrochromium production and consumption.

and Yuzhno-Saranovskoye (Perm Territory), Aganozerskoye (Republic of Karelia) and Sopcheozerskoye (Murmansk Region) – see Table 2. At present chromite ores are mined at Tsentralnoye deposit (the 2017 output stood at 300 thousand tons with the remaining reserves totaling 3,5 million tons (Cr_2O_3 grade of 37.7%) and Glavnoye Saranovskoye (106 000 tons, 4,4 million tons at Cr_2O_3 grade of 39% respectively). The overall commercial chromite-type ore output in Russia stands at 405 000 tons. Cost-effective chromite mining is feasible at Zapadnoye deposit, which is ready for development and which lies immediately next to Tsentralnoye deposit (ore reserves standing at 2.9 million tons at Cr_2O_3 = 39.07%) and Yuzhno-Saranovskoye (2.8 million tons at Cr_2O_3 = 37.7%, respectively). The both deposits have been fully prepared for the development. However, all the mined reserves of high-grade chromite ores, as well as those prepared for immediate development, are likely to be depleted completely in 14–15 years' time which is bound to bring about further increase in the expensive chromium ore imports.

More than half the total chromite reserves of Russia is concentrated at Aganozerskoye deposit (26.6 million tons at 22.65% Cr_2O_3) and Sopcheozerskoye deposit (9.5 million tons at 25.68% Cr_2O_3 respectively). However, no ore mining is done at these deposits due to low chromium grade, unfavorable iron-to-chromium ratio inherent to the ores (Fe: Cr > 3) and lack of cost-effective industrial ore processing technology.

TABLE 2: The main chromite ore deposits of Russia.

#	Deposit name	Reserves (categories ABC_1+C_2), thousand tons	Reserves, % of the total	Average ore grade, Cr_2O_3, %
Allocated reserves				
1	Tsentralnoye	3 467	6,7	37,73
2	Zapadnoye	2 900	5,6	39,07
3	Glavnoye Saranovskoye	4 429	8,5	39,0
4	Yuzhno-Saranovskoye	2 862	5,5	37,67
5	Aganozerskoye	26 588	51	22,65
Non-allocated reserves				
6	Sopcheozerskoye	9 514	18,3	25,68

It is to be noted that the VIMS. in co-operation with the Central Science Research Institute for Ferrous Metallurgy (TsNIIChermet) has developed an ore processing technology for lean chromite ores characterized by unfavorable iron-to-chrome ratio which comprises the following successive processing stages: X-ray concentration, the production of off-grade concentrate (Cr_2O_3/Fe < 3), its roasting followed by magnetic separation yielding chromium concentrate with Cr_2O_3/Fe > 3, followed by the electrosmelting of the latter yielding the final product – low-carbon ferrochromium containing Cr > 65% and C below 0.5% (conforming to the Russian State Standard ГОСТ 4757-91). A similar technology was successfully used to process high-aluminous chromite ores yielding charge chromium containing about 65% Cr (conforming to the Russian State Standard ГОСТ 4757-91) which makes it quite a marketable product for the ferroalloy industry.

A similar chromite ore processing technology has been successfully used at the Kemi deposit in Finland. The technology looks quite applicable for the ore processing at the Aganozerskoye and Sopcheozerskoye deposits.

At the same time, active development of geology prospecting for new chromite ore deposits is needed in order to bring forth the vast resource potential of the prognosticated resources. It is sufficient to say that at the flanks of Aganozerskoye deposit, the size of the prognosticated resources according to P1 ore accounting category is estimated to stand at about 80 million tons. Prospecting for rich chromium deposits (average grade > 37% Cr_2O_3) is already being conducted in prospective areas of the Polar Urals. In addition, the industrial chromite resource potential of ultrabasic massifs of the republics of Buryatia, Tuva and the south part of the Republic of Sakha (Yakutia) where occurrences of chromium spinelides were discovered earlier, needs to be researched in detail.

Ferromolybdenum (over 50% of the total output) is mainly consumed by ferrous metallurgy plants where it is used for the production high-alloyed corrosion-resistant brands of steel. In Russia, 6 800 tons of ferromolybdenum was produced in 2017. out of which some 5 000 tons was exported. The Sorsk ferroalloy works produced 5 000 tons of ferromolybdenum from the Sorsk deposit ore in 2017 while 1 800 tons was produced there from imported concentrates (see Figure 5). Such a small scale of domestic resource use for ferromolybdenum production is caused by restricted domestic demand for the product and the complicated process of its supply to the foreign markets. This is disproportionally low given the size of the domestic molybdenum resource base [1].

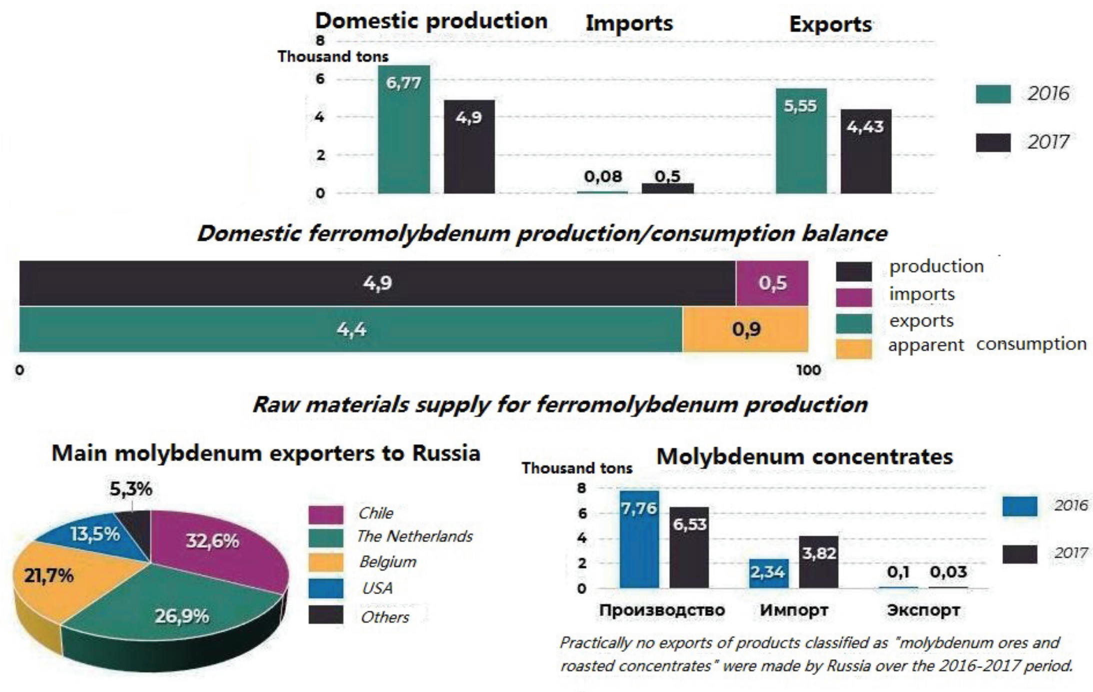

Figure 5: Ferromolybdenum production and consumption.

The Russian resource base for molybdenum comprises 2,1 million tons in total reserves, 1,09 million tons in categories P_1+P_2 prognosticated resources and 2,4 million tons more in category P_3 prognosticated resources. Russian molybdenum deposits are subdivided into two geological industrial types – stockwork deposits of molybdenum proper (Sorskoye, Agaskyrskoye, Zhirekenskoye, Bugdainskoye, Orekitkanskoye and others) and copper-porphyry deposits (Ak-Sugskoye, Peschanka, Malmyzhskoye), the ores of which also contain copper, gold, silver etc.) – for more information see Table 3. However, at present large-scale Sorskoye deposit alone is mined because of low demand for molybdenum and its alloys. The molybdenum grade of the residual ores of that deposit stands at only 0.04–0.06% Mo. It is to be noted that under these circumstances the ore mining was stopped in 2016 at Zhirekenskoye deposit which is combined with a ferroalloy plant specially operated to process the ores of the latter deposit. Molybdenum-proper Bugdainskoye and Orekitkanskoye deposits are not developed either. In contrast to the above information, the development of Ak-Sugskoye deposit of copper-porphyry multimetal ores is under way, with an opencast mine with the ore production capacity of 18,5 million tons per year to be put into commercial operation in 2022/The ore is to be processed at the processing plant to be constructed on the site into gold- and silver-containing copper concentrate and molybdenum-rhenium concentrate. Over the longer term, the development of large multimetal copper-porphyry deposits Peschanka (Chukotka Autonomous district) and Malmyzhskoye (Maritime Territory) where the production of precious metals and copper is envisaged, is bound to meet any domestic demand for molybdenum in Russia, however large it might be in the future, and also to secure leading positions in the world market for this country as a molybdenum exporter.

Table 3: The main molybdenum ore deposits of Russia.

#	Name	Geological industrial ore type	Reserves (categories ABC_1+C_2), thousand tons Mo	Mo reserves, % of the total	Average ore grade, % Mo
Allocated reserves					
1	Sorskoye	stockwork, molybdenum proper	99,6	4,7	0,06
2	Agaskyrskoye	stockwork, molybdenum proper	155,3	7,3	0,05
3	Zhirekenskoye	stockwork, molybdenum proper	61,6	3	0,11
4	Bugdainskoye	stockwork, molybdenum proper	599,7	28	0,08
5	Koklanovskoye	stockwork, molybdenum proper	155,7	7,3	0,082
6	Yuzhno-Shameiskoye	stockwork, molybdenum proper	60,5	2,8	0,07
7	Ak-Sugskoye	copper-porphyry	77,9	3,6	0,015
8	Peschanka	copper-porphyry	98	4,6	0,023
Non-allocated reserves					
9	Lobash	stockwork, molybdenum proper	127,6	6	0,069
10	Malo-Oinogorskoye	stockwork, molybdenum proper	154,9	7,4	0,051
11	Orekitkanskoye	stockwork, molybdenum proper	360,5	17	0,099

When it comes to *titanium-containing metallurgical products*, Russia has been one of the world's leading producers. Over the last few years the leading ferrotitanium producers, mainly PJSC "VSMPO-AVISMA Corporation" and CJSC "Zubtsovsky Machine-Building Works", have practically ceased the production of high-grade ferrotitanium from natural titanium raw materials, switching instead to the use of titanium-containing technogenic wastes and tailings sourced from various machine-building and metallurgical plants. The only exception is the Klyuchevskoy works still using titanium ore concentrates to produce low-grade ferrotitanium (see Figure 6).

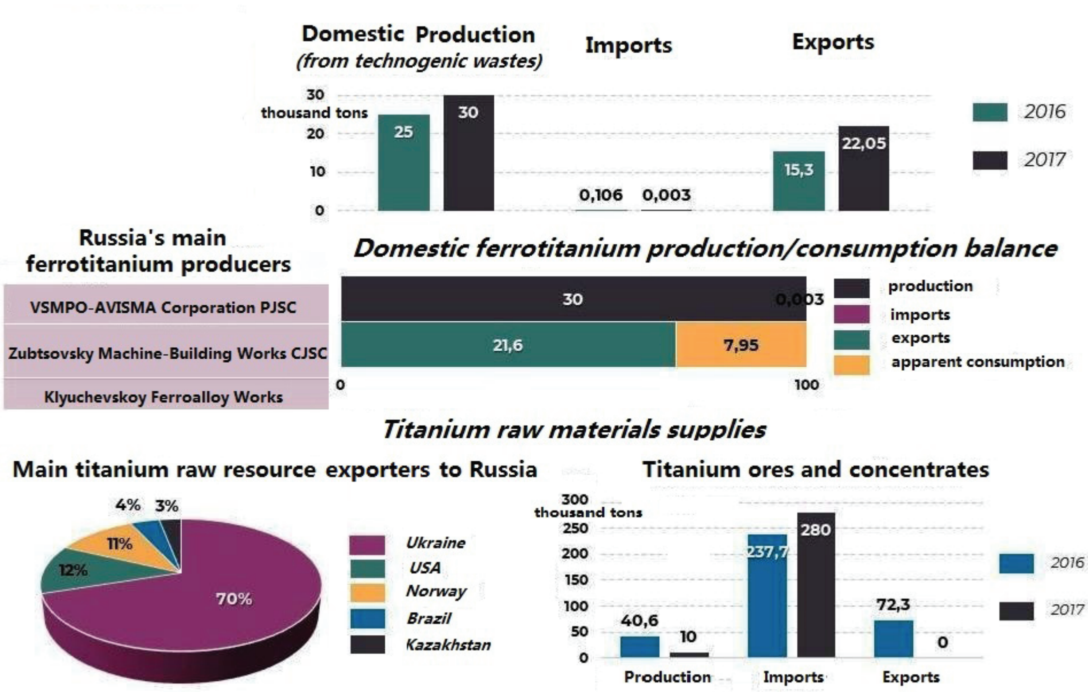

Figure 6: Ferrotitanium production and consumption.

In both cases described above, the ultimate prime source of titanium from which a wide array of specialty products (titanium-containing ferroalloys, titanium sponge, pigment concentrate etc.) is Russia's vast titanium resource base which is one of the world's largest. The titanium ore reserves of all categories (A, B, C_1 and C_2) total 601,2 million tons TiO_2 while the prognosticated resources of categories P_1-P_2 stand at 833,6 million tons TiO_2, of category P_3 – 194,4 million tons respectively [2]. Russia's main titanium deposits' geological industrial types are ilmenite-titanium magnetite one (Yugo-Vostochnaya Gremyakha, Kruchininskoye, Kuranakhskoye, Medvedevskoye, Bolshoy Seyim etc.), alluvial one (Tsentralnoye, Beshpagirskoye, Lukoyanovskoye, Tuganskoye, etc.) and loparite one (Lovozerskoye). Also, a distinctly specific geological industrial type is observed at very large Yaregskoye deposit (leucoxene-quartz weakly-lithified oil-bearing sandstone, see Table 4). The details on the deposits described above are summarized in Table 4. However, only the Lovozerskoye deposit is mined.

Table 4: The main titanium ore deposits of Russia.

#	Name	Geological industrial ore type	Reserves (categories ABC_1+C_2), thousand tons TiO_2	TiO_2 reserves, % of the total	Average ore grade, % TiO_2
Allocated reserves					
1	Yaregskoye	leucoxene-quartz oil-bearing sandstone	278 654	46,4	10,44
2	Medvedevskoye	ilmenite-titanium magnetite	30 209	5,0	7,03
3	Bolshoy Seyim	ilmenite-titanium magnetite	22 462	3,7	7,67
4	Lovozerskoye	loparite	8 355	1,4	1,29
5	Tuganskoye	zircon-rutile-ilmenite, alluvial	2 501	0,4	19,69 kg/m^3
Non-allocated reserves					
6	Yugo-Vostochnaya Gremyakha	ilmenite-titanium magnetite	49 794	8,3	8,55
7	Kruchininskoye	apatite-ilmenite-titanium magnetite	50 019	8,3	8,39
8	Beshpagirskoye	zircon-rutile-ilmenite, alluvial	528	0,1	24,75 kg/m^3
9	Tsentralnoye	zircon-rutile-ilmenite, alluvial	6 396	1,1	24,6 kg/m^3

At the same time, the domestic demand for titanium is very high: the metallurgy industry alone (titanium sponge production, in particular) annually requires some 100 000 – 110 000 tons of TiO_2 while the pigment production at the newly acquired Crimean plant needs over 100 000 tons of TiO_2 each year. Also, the production of welding electrodes requires an extra 10 000 tons of TiO_2 annually [2]. However, only 2 200 tons of titanium dioxide per year is produced at the Solikamsk magnesium plant from loparite concentrates while the remaining amount of the source ore is imported, chiefly from Ukraine. The main causes of the practical absence of titanium ore production in Russia are inferior quality of domestic titanium ores and problems arising from resource management shortcomings.

The chief problem hampering the development of titanium-magnetite ore deposits with which over 80% of Russia's titanium resources is associated is lack of industrially applicable technology for the processing of titanium-magnetite concentrates obtained along ilmenite ones during primary ore separation stages [5]. Ilmenite concentrates are an excellent source material for the production of the pigment concentrate and various materials used in the metallurgy. As regards modern pyrometallurgy processes, the use of titanium-magnetite concentrates greatly complicates the key process of blast-furnace smelting. Because of this, titanium-magnetite concentrates are considered industrial waste, which, in turn, leads to a considerable increase in the net costs of titanium products thereby decreasing the investment appeal of industrial development of titanium-magnetite type ore deposits. Also, similar mineralogical and technological issues are preventing the start of the development of the giant Yaregskoye deposit: efficient industrial processing technologies applicable to leucoxene-type titanium ores are not developed neither in this country nor abroad.

For all the reasons described above, the titanium ore production in Russia is practically non-existent. The full-scale commercial development of the alluvial-type Tuganskoye deposit can become the top-priority imports substitution step in the titanium resource field. At present, that deposit is already mined on a trial scale, and if the design capacity is reached 60 000 tons of ilmenite concentrate will be produced there annually. That amount is enough to meet about 20% of the domestic demand for titanium, while the subsequent development of Tsentralnoye, Beshpagirskoye and other alluvial-type deposits will succeed in narrowing the supplies gap and reducing the imports still further.

Another task requiring most detailed attention is developing a cost-effective industrial technology for the combined pyro- and hydrometallurgical conversion of lean titanium-magnetite concentrates (3 – 4% TiO_2) into low-titanium slag and ferrotitanium as the end product. The successful development and commercialization of such a technology will pave the way for the effective development of large endogenous titanium-magnetite deposits like Yugo-Vostochnaya Gremyakha, Bolshoy Seyim etc.

As regards geology prospecting for titanium ores, the identification and assessment of high-titanium ilmenite-proper ore reserves similar to Ariadna deposit (Maritime territory) is highly actual. In this direction, geology prospecting forecast operations are conducted in prospective structures in Karelia-Kola region, South Yakutia and the south parts of the Russian Far East. The successful solution of these technological and geology prospecting tasks is bound to both increase the quality of the domestic titanium resource base and to add to the investment appeal of the domestic titanium deposits.

The production of *ferroniobium* which is used as a universal alloying additive to low-alloy high-tensile sorts of steel used for the production oil and gas pipelines, structural elements in civil engineering and in the machine-building applications, is non-existent in Russia. This expensive, high-demand ferroalloy is exclusively imported (about 5 000 tons per year) from Brazil (some 90% of the total imports) and other foreign countries (see Figure 7).

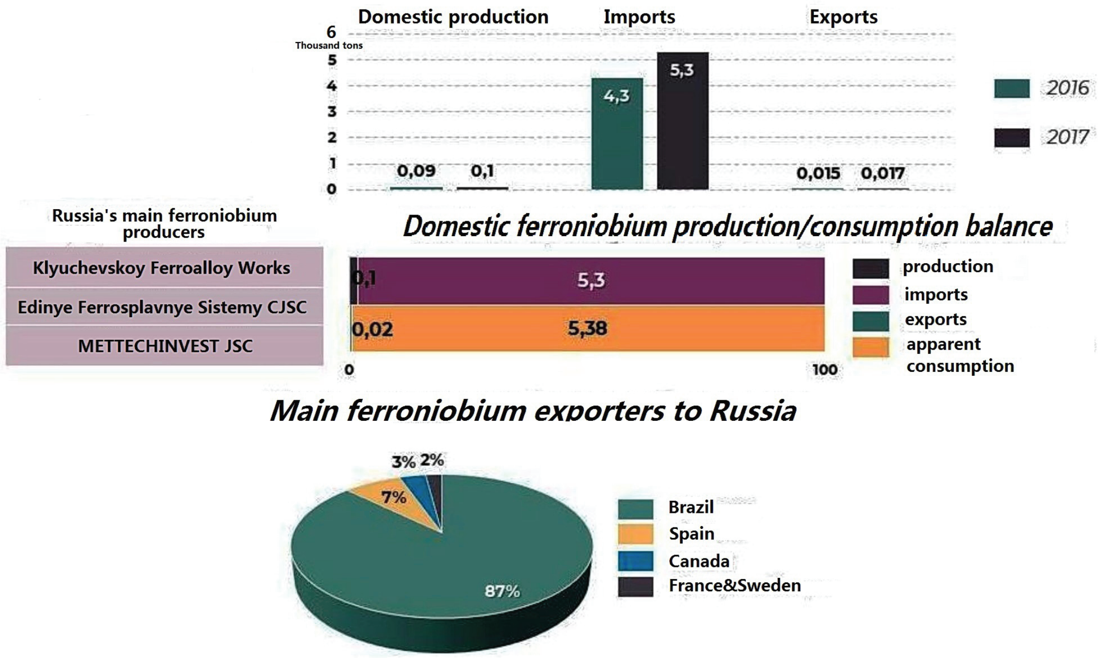

Figure 7: Ferroniobium production and consumption.

At the same time, Russia possesses a vast mineral base for niobium, represented by a considerable number of multimetal rare-metal deposits [1]. The most prominent among these are large objects associated with carbonatite weathering crusts (Tomtorskoye, Chuktukonskoye, Beloziminskoye deposits) and nepheline syenites containing loparite (Lovozerskoye and Bolshetagninskoye deposits, see Table 5). In addition, some smaller-scale deposits containing, along with niobium, tantalum, uranium, REEs and other rare metals, have been discovered and measured in the Siberian region. Among these, Zashikhinskoye, Katuginskoye, Ulug-Tanzekskoye and some other deposits can be mentioned. Of primary importance is the development of Tomtorskoye deposit, one of the world's biggest ore entities of its kind, which ores contain, along with niobium, also REEs and scandium in commercial grades. It is sufficient to point out that the ores of the Buranny area of that deposit display Nb_2O_5 grades of about 4% which substantially exceeds those observed at Brazil's Arasha deposit which is currently meeting about 80% of the world demand for niobium. Buranny area ores are essentially a natural niobium ore concentrate the long-distance transportation of which to the advanced processing plants is unarguably cost-effective. Preliminary estimates have shown that the industrial development of the Buranny area alone will completely meet the domestic demand for not only niobium but also for scandium and REEs, including for the ferroalloy production, for decades ahead.

Table 5: The main niobium ore deposits of Russia.

#	Name	Geological industrial ore type	Nb_2O_5 reserves, % of the total	Average ore grade, % Nb_2O_5
Allocated reserves				
1	Lovozerskoye	nepheline syenites with loparite	22,9	0,25
2	Katuginskoye	primary zircon-pyrochlore-loparite	8,79	0,35
3	Tomtorskoye	residual carbonatite weathering crust containing pyrochlore	1,14/17,68	3,99
Non-allocated reserves				
4	Chuktukonskoye	residual carbonatite weathering crust containing pyrochlore	0,58/6,4	0,74
5	Bolshetagninskoye	nepheline syenites with loparite	5,88	0.98
6	Beloziminskoye	carbonatites (silicate metasomatites)	33,61	0,35

Ferrovanadium is by far the most important component for the production of quality sorts of steel. Over 12 000 tons of ferrovanadium is produced annually in Russia, with the entire output consumed by the domestic metallurgical plants. The Russian mineral resource base is quite vast. It is represented chiefly by titanium-magnetite deposits the ores of which contain vanadium as a by-product metal, with grades of about 0,n %. Besides, Srednepadminskoye deposit of vanadium proper has been discovered and estimated in the Republic of Karelia, the average grade being V_2O_5 = 2.7%. It is important to note that the ores of that deposit also contain uranium and gold as by-product elements. Meanwhile, the main source of vanadium in Russia is vanadium slags forming during the pyrometallurgical processing of titanium-magnetite ores. In particular, the steel and crude iron smelting from the titanium-magnetite ores of Kachkanarskoye and Suroyamskoye deposits (both situated in the Urals region) yields vanadium slags containing some 25% V which are used for the production of all the required ferrovanadium. It looks clear that this vanadium source is fully capable to meet both the current and the projected demand for ferrovanadium in Russia.

Small amounts of *ferrotungsten* (about 3 000 tons per year) are also produced in Russia. Ferrotungsten imparts special hardness to instrumental-grade sorts of steel. Some 2 000 tons of domestically produced ferrotungsten are exported annually. The mineral resource base for tungsten in Russia is great (1,3 million tons in the reserves and resources of all categories combined). It consists predominantly of skarn scheelite geological industrial type, such as Tyrnyauzskoye (Kabardino-Balkar Republic), Vostok-2 and

Lermontovskoye (Maritime Territory), Agylkinskoye (Republic of Sakha (Yakutia) etc. [1]. The biggest deposit in Russia is Tyrnyauzskoye (the reserves amounting to 209 500 tons WO_3). Its ores are characterized by low tungsten grades in the ores (0,44%). At present, only a single small area of the deposit is being developed. Commercial tungsten ore mining in Russia is currently done only at three deposits – Spokoinenskoye (Transbaikal Territory) with the ore grade of 0,22% WO_3, and Lermontovskoye and Vostok-2 the both of which comprise rich ores with the WO_3grades of 2,46% and 4,4%, respectively. The aggregate production volume of WO_3 in Russia stands at 3 500 tons per year. While mined according to the current tungsten concentrate production parameters, the rich ore reserves at the above deposits are expected to get depleted within 7 – 10 years. Consequently, the intensification of prospecting for new tungsten deposits is needed in Maritime Territory where there exists a potential for the discovery of new hidden objects of the Lermontovskoye and Vostok-2 type.

Ferronickel is the most important component for the production of stainless and heat-resistant grades of steel. However, the falling demand for such special sorts of steel observed over the last decades caused the domestic ferronickel production to linger at several thousand tons per year, out of which about 2 000 tons per year of the alloy is exported. Russia is one of the leading world producers and exporters of both raw and refined nickel metal. Nickel is also used in areas other than metallurgy – for the production of electrotechnical devices, accumulators and batteries, catalysts, etc. A sharp increase in the demand for nickel is forecast both worldwide and in Russia in connection with the shift to renewable energy generation and battery-driven vehicles and electromobiles production, all of which use nickel as a crucial battery material.

Russia's resource base is sufficiently great, totaling about 7,5 million tons of nickel, just at endogeneous deposits already commercially mined. It puts Russia on an equal footing with the world's leading nickel producers such as the Philippines, Australia, Canada and others [1]. The bulk of Russia's nickel reserves is associated with huge sulfide copper-nickel deposits of Norilsk and Pechenga areas, operated by PJSC "Norilsk Nickel". Considerable nickel reserves are represented by laterite (silicate) type nickel-cobalt deposits of the Urals region such as Serovskoye, Buruktalskoye, Tochilnogorskoye and other deposits. Laterite-type nickel deposits display nickel grades similar to those seen at the copper-nickel sulfide ones, yet they tend to be near-surface and easily eligible for open-pit ore mining with subsequent heap leaching of nickel, and also for in-situ mining. Thus, the size of the Russian nickel resources is more than sufficient to meet the nickel demand for all applications, including the ferroalloy production, for many decades ahead.

Conclusion. To sum up the article, it has to be noted that the domestic mineral resource base of molybdenum, niobium, vanadium and nickel looks both quantitatively and qualitatively sufficient to meet the demand for the production of the respective ferroalloys in the long term, which will enable to completely substitute for the imports in conditions of possible future increasing demand. The mineral resource base of manganese, chromium and tungsten is characterized by low-quality ores at the main resource objects, while domestic endogeneous titanium resources feature extremely complex mineral composition. To cope with those challenges, on one hand, the development and commercialization of new highly efficient technologies for the processing of inferior, lean and medium-grade ores is needed, and, on the other hand, highly actual is the active development of geology prospecting for the identification and assessment of new mineral resource objects characterized by acceptable technological and economic indicators to ensure their successful commercial development.

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