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RESEARCH PAPER

Study on the synthesis of FeCrMnSi ferroalloy using technogenic raw materials

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ABSTRACT

The article explores the potential for utilizing technogenic waste – chromium and manganese dust as well as coal slurry – to produce a novel complex FeCrMnSi ferroalloy used for steel alloying and deoxidation. A technical and chemical analysis of the investigated waste materials was conducted. These materials are fine-grained products, necessitating their briquetting into a single charge. Laboratory experiments were carried out to smelt the chromium-manganese-silicon ferroalloy at 1750°C (50°C above the theoretical melting point), resulting in experimental samples of the complex ferroalloy with the following average composition (in %): 40.80 Cr, 19.44 Mn, 9.75 Si, 25.44 Fe, and 4.53 C. The study's findings demonstrate that the waste materials possess the necessary characteristics for producing high-quality ferroalloys, highlighting the potential to reduce dependence on expensive raw materials.

Keywords: chromium; manganese; dust; coal slurry; ferroalloy; recycling

INTRODUCTION

Metallurgy is one of the most resource-intensive industries with large-scale global production volumes. The efficient operation of vast production capacities is possible only with high-quality metallurgical raw materials, reserves of which are rapidly depleting. Despite the steady growth in global mineral extraction, according to various researchers, only 10% of the raw materials extracted from the earth are converted into finished products. In comparison, 90% ends up as waste, forming technogenic by-products. Previously, such waste was primarily considered a source of environmental hazards; however, today, it is of interest to extract valuable components [1, 2].

One such valuable technogenic by-product is the dust generated during the production of high-carbon ferrochrome. This dust comprises a mixture of fine particles of ore, coke, and other materials charged into the furnace. It forms during mechanical crushing, material preparation, charging, and abrasion of the charge, as well as during the high-temperature ferroalloy production process [3-6].

When producing ferrochrome in an open furnace, the dust content in the off-gas reaches 50–60 g/m³; in some cases, it can go as high as 100 g/m³. In a closed furnace, due to increased pressure under the furnace roof, the dust content of the off-gas is lower, ranging from 15–20 g/m³. The specific dust yield per ton of ferrochrome is 50–150 kg/t for open furnaces and 25–75 kg/t for closed furnaces [7, 8].

A similar issue of fine-grained waste accumulation occurs in the production processes involving manganese raw materials. These wastes also form during metallurgical processing (extraction, crushing, beneficiation, transportation, and smelting) and accumulate in large quantities in dumps, sedimentation ponds, and storage facilities, occupying vast areas and causing numerous environmental and economic challenges [9, 10].

Using such fine fractions in metallurgical processes complicates smelting and increases energy consumption for ferroalloy production [11, 12]. Additionally, the draft system carries fine-grained materials out of ferroalloy furnaces, continuing to circulate in the technological cycle and overloading gas cleaning and aspiration systems [13].

Another type of waste potentially suitable for metallurgical processing is coal waste, which forms during coal extraction and beneficiation in water-saturated slurry and fine sludge (a fine-grained, high-ash product). In addition to the organic matter of coal, the solid component of such waste contains 30–80% mineral content. These wastes also have a high moisture content—up to 50% – which significantly complicates their disposal and utilization [14, 15].

Current coal slurry processing methods remain inefficient. Traditionally, coal slurry from beneficiation plants is separated from slurry water in pyramid-shaped settling tanks and thickening cones, while the overflow water is returned to the beneficiation cycle. The thickened product is dehydrated using screens and sedimentation centrifuges. The dehydrated slurry is then added to unprocessed screenings and used as non-standard fuel, which does not represent an efficient or rational use of this product [15-17].

In recent years, slurry formation has significantly increased due to factors such as higher ash content in extracted coal and the presence of fine particles. Mechanized settling tanks are no longer sufficient, prompting beneficiation plants to construct earth-based sedimentation ponds (slurry storage facilities) for additional slurry collection [18].

These storage facilities occupy large areas around coal enterprises, removing land from economic use and immobilizing part of the funds invested in coal extraction and processing. Additionally, they contribute to environmental pollution [19]. For instance, Kazakhstan extracts approximately 100 million tons of coal annually, implying significant amounts of coal slurry [20].

FeCrMnSi typically contains 15–35% Mn, 20–40% Si, 20–30% Cr, and less than 0.5% C. For example, such alloys produce steels with high chromium and manganese content, whereas low-carbon FeCr and FeSiCr are traditionally employed.

FeCrMnSi can be obtained by various methods, including smelting different ferroalloys as sources of key elements, reducing high-MnO slag and a lime-chromite FeSiCr melt, simultaneous reduction of Mn, Cr, and Si sources with carbon, and reduction of manganese metal production waste slag (containing 10–14% MnO) using FeSiCr. Industrial practice demonstrates the feasibility of producing FeCrMnSi with a 0.01–0.013% phosphorus content. This alloy remains stable during storage [21-23].

Kazachkov and Melikaev's work has made theoretical and practical advancements in the production of chromium-manganese-silicon ferroalloys. Their research developed a single-stage smelting process based on carbon reduction of iron, chromium, manganese, and silicon oxides from a mixture of chromium and manganese ores [24]. This classical process served as the foundation for the technology used in this study.

Previous studies also explored the production of FeCrMnSi via carbothermic reduction of manganese and chromium ores using high-ash coal, which simultaneously acted as a silicon source. This approach yielded an alloy with the following composition: 14.85% Fe, 14.05% Si, 7.55% Mn, 57.54% Cr, and 6.01% C, with $P < 0.03\%$ and $S < 0.02\%$ [23].

This study investigates the feasibility of producing a complex FeCrMnSi ferroalloy from the aforementioned technogenic waste. Incorporating such materials into metallurgical processes helps address waste disposal issues, improves the metallurgical industry's environmental sustainability, and expands the raw material

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base for ferroalloy production, enabling the creation of a competitive complex alloy. This complex ferroalloy is a mixture of various proportions of chromium, manganese, and silicon used for steel deoxidation and alloying. It serves as an alternative to silicomanganese, ferrosilicon, and ferrochrome.

MATERIAL AND METHODS

Raw materials

To develop a technology for producing FeCrMnSi (chromium-manganese-silicon) ferroalloy, the primary charge materials included the following Kazakhstani technogenic waste: Cr and Mn dust and coal slurry.

The chemical composition of the charge materials was determined using classical wet chemical analysis, including gravimetric and volumetric methods. The coal slurry's technical analysis (ash, moisture, volatiles, and fixed carbon) was also performed according to standard proximate analysis techniques. **Table 1** and **Table 2** present the chemical and technical compositions of the investigated charge materials, which include Cr dust from the production of high-carbon ferrochrome at the "Aktobe Ferroalloy Plant" of JSC "TNC Kazchrome," Mn dust from silicomanganese production at the "Aksu Ferroalloy Plant" of JSC "TNC Kazchrome," and coal slurry from the Karaganda region, used as a reductant.

Cr dust was mainly composed of chromium spinel ($FeO \cdot Cr_2O_3$) and magnesia olivine (Mg_2SiO_4), while Mn dust mainly consisted of manganosilicate phases (e.g. rhodonite, $MnSiO_3$) and quartz. Both dusts had minor but noteworthy impurities: e.g. 0.4–0.8% Zn and traces of Na, K, Cl, P, S.

Microsilica (silica fume) (SiO_2 > 95%) was additionally introduced partly as a binder and an additional source of Si.

Table 1 Chemical composition of charge materials, wt %

Material	Cr_{total}	Mn_{total}	Fe_{total}	SiO_2	CaO	MgO	Al_2O_3	Zn	Cl	Na	K	C	S	P
Cr dust	18,0–20,0	–	5,0–8,0	13,0–19,0	2,0–8,0	28,0–30,0	5,5–7,0	0,4 – 0,6	0,7-0,8	1,2 – 1,4	0,6 – 0,8	2,3 – 2,8	0,8–2,7	0,015–0,040
Mn dust	–	30,0–32,0	2,0–3,0	30,0–34,0	4,0–5,0	0,5–2,0	5,0–7,0	0,5 – 0,8	3,2 – 3,3	0,1 – 0,2	1,0 – 1,2	1,0 – 1,2	0,1–0,2	0,05-0,06

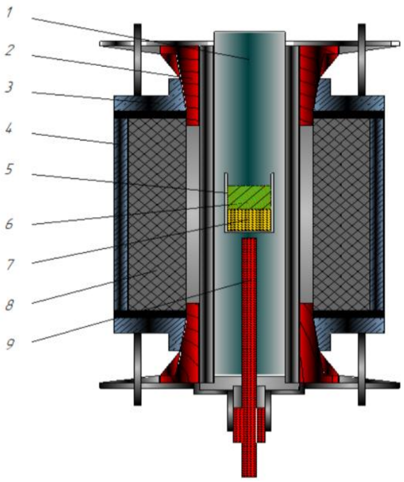
Table 2 Technical composition of coal slurry and chemical composition of its ash, wt %

Technical composition	A	W	V	C_{solid}			
	35,0–40,0	1,0–2,0	15,0–20,0	43,5–45,0			
Chemical composition of the ash	Al_2O_3	SiO_2	CaO	MgO	Fe_2O_3	S	P
	34,0–38,0	57,0–60,0	1,0–2,0	1,5–2,5	3,5–5,0	0,3–0,5	0,05–0,06

Smelting of alloy

Based on the physicochemical studies of the aforementioned charge materials and the thermodynamic modeling results from previous research on chromium-manganese-silicon ferroalloys [25], experiments were conducted to investigate the feasibility of smelting the alloy under laboratory conditions. These studies focused on evaluating the behavior of the charge materials at high temperatures and determining the optimal conditions for producing high-quality chromium-manganese-silicon ferroalloy, thereby improving efficiency and process control during smelting.

The chromium-manganese-silicon ferroalloy was experimentally smelted in a high-temperature Tamman furnace, depicted in **Fig. 1**.



1 – graphite tube; 2 – water-cooled copper plates; 3 and 4 – water-cooled housing; 5 – crucible; 6 – slag; 7 – metal; 8 – fireproof body; 9 – thermocouple

Fig. 1 High-temperature resistance furnace (Tamman furnace)

This high-temperature furnace features a heating mechanism consisting of a graphite tube as the active workspace. Temperature regulation within the furnace is achieved through a thyristor voltage regulator integrated into the primary winding of the power transformer. This setup enables the application of several thousand amperes of current to the output buses at a low voltage range of 0.5 to 15.0 V. Temperature measurements were conducted using a tungsten-rhenium thermocouple, model TR-5/20, positioned at the crucible's base within a reinforced corundum enclosure [23]. The crucible is secured from above using tungsten wire, ensuring stable positioning above the thermocouple.

The primary goal of the laboratory experiments was to completely reduce all oxides in the charge during smelting. This allowed for an evaluation of the efficiency of the reduction reactions and the behavior of the charge materials at high temperatures.

Briquetting process

Briquetting, a simple and effective method for agglomerating fine-grained raw materials, was conducted using a laboratory hydraulic press model TY50001. The press is equipped with a hydraulic cylinder with a pressure gauge and a maximum force capacity of 50 tons.

A series of briquetting experiments was conducted to prepare a batch of agglomerated charge material and determine the optimal briquetting parameters. Each briquette weighed 29–30 grams, had a diameter of 35 mm, and was 15 mm high.

The total binder content accounted for 10% of the charge mass. The primary binders used included water and an aqueous liquid glass solution with concentrations of 5, 10 and 15%. The briquetting pressure was set at 10 tons.

After pressing, the briquettes were dried in open air and in a furnace at temperatures up to 200°C for 2 hours. Post-drying, the briquette weight decreased by 8–10%, indicating the moisture loss in the coal slurry and the binder.

The final composition of the mono-charge subjected to briquetting was as follows (in %): Cr dust 36.4, Mn dust 36.4, coal slurry 18.2, microsilica 9.1.

Mechanical Strength Testing

Fig. 2 presents the overall scheme of briquette preparation, which included dropping, sieving, and weighing fragments to assess mechanical strength.

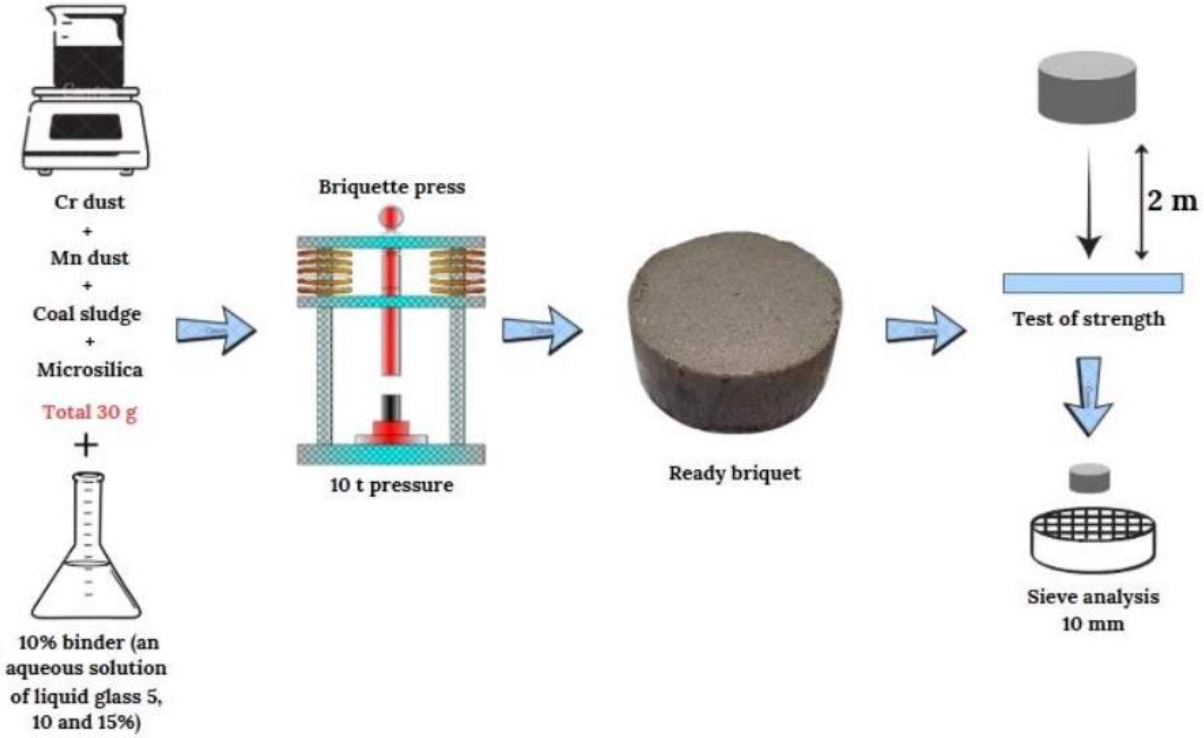


Fig. 2 General view of the technological scheme for briquette production

The briquettes were required to exhibit a high level of mechanical strength. Therefore, after natural drying, they were tested for mechanical strength using the drop method on a specialized apparatus in accordance with GOST 21289-75 "Coal Briquettes. Methods for Determining Mechanical Strength." This method assesses the strength characteristics of briquettes under mechanical loads, which is crucial for their subsequent transportation, storage, and use in ferroalloy smelting processes.

During testing, the briquettes were dropped onto a metal plate from a height of 2 meters three times. After each drop, the broken pieces were sieved through screens with mesh sizes of 10 mm and weighed. This process allowed for the evaluation of the extent of briquette destruction and its resistance to mechanical damage.

RESULTS AND DISCUSSION

Based on the analysis of the chemical and technical composition, technogenic wastes such as Cr dust and Mn dust demonstrate significant potential as substitutes for traditional ores, due to their suitability as sources of chromium and manganese, as well as their low levels of harmful impurities (S and P). However, the relatively low Cr (18–20%) and Mn (30–32%) content necessitates the processing of larger volumes, while the high levels of MgO and SiO_2 may complicate slag formation. Coal slurry, as a carbonaceous material, features low sulfur content (0.3–0.5%) and moderate levels of volatile matter (15–20%), making it advantageous for creating a reducing atmosphere in furnaces. Nevertheless, its high ash content (35–40%) and low carbon content (43.5–45%) limit its efficiency compared to traditional reductants such as coke and anthracite. Therefore, effectively utilising these materials requires adapting metallurgical technologies and their integration with traditional raw materials.

Based on previously obtained thermodynamic data [23], the optimal composition of the charge mixture was determined, with a 5% excess of solid carbon above the stoichiometric requirement. The temperature range for metal formation was established as 1500–1800°C for smelting FeCrMnSi ferroalloy in a high-temperature resistance furnace. The predicted composition of the FeCrMnSi ferroalloy at equilibrium (1800 °C, 5 % excess C) was as follows (in %): Cr – 35.84; Mn – 24.47; Si – 16.25; Fe – 22.63.

The thermodynamic prediction of the FeCrMnSi ferroalloy composition was initially performed for a charge consisting of more traditional raw materials. However, since the fundamental reduction mechanisms and element recovery patterns remain consistent, the obtained results serve as a reliable reference for estimating the expected alloy composition in this study. The replacement of natural Cr and Mn ores with Cr and Mn dust from ferrochrome and silicomanganese production, along with micro silica as an additional silicon source, does not significantly alter the overall thermodynamic behaviour of the system. Therefore, the predicted composition reasonably approximates the final alloy chemistry under the given smelting conditions.

Optimization of briquetting parameters

Briquettes were prepared using chromium dust, manganese dust, and coal slurry to produce the FeCrMnSi ferroalloy. Drop tests revealed that briquettes using pure water or a 5% aqueous liquid glass solution as a binder exhibited the lowest strength. The yield of usable material (fractions larger than 10 mm) was 75–80% after three drops. In contrast, briquettes prepared with 10% and 15% aqueous solutions of liquid glass, with a total binder content of 10% of the charge weight, demonstrated superior strength, with a yield of fractions larger than 10 mm in the range of 90–95% after three drops. These results indicate that such briquettes meet the requirements for charge materials and are suitable for use in ferroalloy production furnaces.

The briquettes were loaded into a graphite crucible. The smelting was conducted at 1750°C with a holding time of 15 minutes. During smelting, no active gas evolution was observed, indicating the stability of the reactions. Figure 3 shows the appearance of the chromium-manganese-silicon ferroalloy products obtained during this experiment.

Since the input materials are inhomogeneous, each experiment was repeated three times to ensure reproducibility.

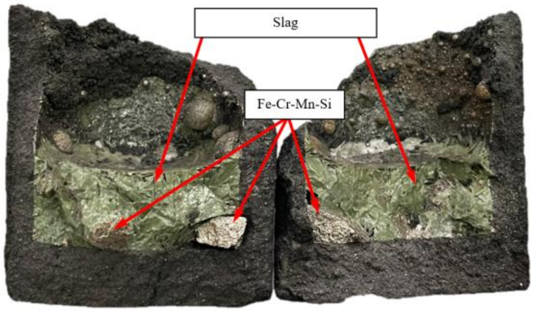


Fig. 3 Products of high-temperature smelting of Fe-Cr-Mn-Si ferroalloy

Fig. 3 displays a cross-section of the graphite crucible containing the smelting products obtained during one of the experiments for producing chromium-manganese-silicon ferroalloy. The image clearly shows the separation of smelting products into metal (golden particles) and slag (a solid green mass), a critical aspect of the ferroalloy production process.

Alloy composition

According to the results of analytical chemistry, the composition of the metal and slag is as follows: metal, %: 40.80 Cr; 19.44 Mn; 9.75 Si; 25.44 Fe; 4.53 C; S 0.02; P 0.02; slag, %: 6.09 Cr_2O_3; 1.71 MnO; 1.03 FeO; 39.78 SiO_2; 26.27 Al_2O_3; 6.14 CaO; 18.38 MgO. The slag is a solid, stone-like material, preventing disintegration (also after storing in the open air for more than 30 days), which facilitates its transportation and storage.

The composition of the produced alloys showed slight variations within acceptable limits during the experimental smelting trials, primarily influenced by the natural fluctuations in the raw material composition. However, the overall trends in element distribution remained consistent across all trials, confirming the reliability of the proposed process.

The discrepancy between the actual alloy composition and the predicted values (calculated using data from the HSC Chemistry 6 database—a resource based on and continually updated by SGTE [23]) can be attributed to active interactions with the atmospheric environment during the smelting process, which significantly impacts the alloying process. Additionally, the graphite crucible contributes to the reduction and carburization of the alloy.

It is noteworthy that the obtained alloy composition differs from similar standard FeMnSiCr ferroalloys, which typically contain (in %): 20–30 Cr, 15–35 Mn, 20–40 Si, <0.5 C, and the balance Fe [21].

The actual alloy contained higher Cr (≈40.8% vs 35.8%) and higher Fe, but notably lower Mn and Si than predicted. This discrepancy can be attributed to several factors:

1) Slag chemistry – the waste materials introduced a large amount of MgO and Al_2O_3 (from the dusts) and SiO_2 (from both dust and microsilica) into the system. These oxides form a high-melting slag that likely retained some manganese and silicon. In particular, silica requires the highest temperature and strongest reducing conditions to convert to Si metal, so any slight shortfall in effective carbon or local temperature would preferentially leave Si in the slag as silicate. Manganese, while easier to reduce than Si, can also be partially absorbed in slag as MnO or escape as vapor at these temperatures if not captured by the alloy.

2) Reduction kinetics and time – the 15-minute hold, although sufficient to form metal, may not have achieved complete equilibrium. It's possible that chromium, being derived from Cr_2O_3 (which reduces at relatively lower temperatures into metal or stable carbides), was reduced earlier and more completely. Silicon reduction (from SiO_2 to SiC/Si) typically occurs last and may have been incomplete in the given time. Thus, the alloy ended up Cr-rich and Si-lean relative to the equilibrium expectation.

3) Excess carbon and crucible effect – the use of a graphite crucible and 5–10% excess reducer ensured strong reducing conditions, which favor chromium reduction (as Cr_2O_3 is readily reduced to Cr metal at ~1600 °C). The crucible also continuously supplied carbon, which may have helped drive Cr and Fe reduction beyond the model's stoichiometric scenario. Still, at the same time, this extra carbon drove more carbide formation than increasing Si yield.

Despite these differences, the overall recovery of metals was quite high. Essentially all chromium and iron from the dusts were captured in the alloy, and a majority of manganese was as well (with a minor shortfall likely sequestered in the slag). This indicates a reduction efficiency for Cr and Fe up to 90%, and for Mn on the order of 80–90%. Silicon's recovery was lower (under 50% of the potential Si in the charge was in the alloy), which is typical for one-stage processes unless very high temperatures or silicon-specific reductants (like aluminum or silicon carbide) are used.

The slag contained most of the unreduced silica and MgO, Al_2O_3, CaO from the dusts and coal ash, forming a stable calcium–magnesium aluminosilicate matrix (the solid green mass observed). This slag effectively trapped impurities such as phosphorus and sulfur. The initial P content of the dusts was low (~0.02–0.06% in total) and final alloy phosphorus was not detectable beyond ~0.02%, consistent with industrial reports of FeCrMnSi achieving P ~0.01%. Sulfur largely volatilized as CS_2/SO_2 or was absorbed in the slag; the alloy's S content remained low (<0.05%), which is important for steel quality. Another impurity, zinc, present in the dusts (up to 0.8%), would have vaporized at the smelting temperature (Zn boils at ~907 °C). This highlights a benefit of the process: volatile contaminants are removed from the metal phase. However, they would need to be managed in the off-gas system in an industrial setting (e.g. captured in dust collectors). In summary, the reduction process was efficient for the major metals. The presence of abundant basic oxides (MgO, CaO) in the charge helped to form a slag that scavenged harmful impurities (P, S, alkalis) and protected the alloy's quality.

The carbon content is a key difference when comparing the obtained alloy to standard FeCrMnSi ferroalloys. Industrial FeCrMnSi is usually low-carbon (<0.5% C), making it suitable for low-carbon steel production. FeCrMnSi containing ~4.5% C, would be classified as a high-carbon complex alloy. The high carbon was anticipated given carbon reductants and a graphite crucible. The carbon content obtained is comparable to typical high-carbon ferrochrome or ferromanganese. While this is not an issue for certain applications (for example, deoxidation of steel can tolerate carbon, and high-carbon steel alloying can directly use high-C additions), it may limit the direct use of the alloy in producing ultra-low-carbon steels or stainless steels. Fortunately, metallurgical industry has established refining techniques to decarburize high-carbon alloys. For instance, high-carbon ferrochrome is often refined via oxygen blowing or vacuum treatment to produce low-carbon ferrochrome. Similar processes (oxidative refining in a converter or vacuum induction melting) could be applied to the FeCrMnSi alloy to reduce its carbon content to below 0.5% if required. It is worth noting that the presence of ~10% Si in the alloy is beneficial in that silicon helps the decarburization reactions (Si is preferentially oxidized, releasing heat and facilitating C removal). Thus, from an industrial perspective, the high carbon content is not a fundamental obstacle but rather an aspect to manage in subsequent processing. In fact, producing the alloy in a high-C state may be thermodynamically easier and then adjusting carbon later might be more efficient than trying to directly smelt a low-C alloy (which would risk lower Cr yields or require expensive low-C reductants).

Overall, the experimental results validate the feasibility of waste-to-ferroalloy production. It was demonstrated that even with 100% waste-derived feed (no fresh ore), it is possible to obtain a complex alloy that is compositionally in line with known FeCrMnSi alloys, except for carbon. The alloy's Cr (~41%) and Mn (~19%) contents fall in a range useful for alloying high-Cr, high-Mn steels, and the Si content (~10%) is sufficient for it to act as a deoxidizer (many standard deoxidation alloys have 10–30% Si). The slightly lower Mn and Si compared to target could be adjusted by tuning the charge ratio (e.g. adding more manganese dust or silica fume in the briquette if a higher Si content alloy is desired) or by increasing the smelting temperature/time to improve Si recovery. The findings also highlight the impact of gangue content in the waste: high MgO/Al_2O_3 leads to a viscous slag that might have retain some Si/Mn. In an industrial electric furnace, operators could add fluxes (like CaO) to optimize slag viscosity and improve metal separation, potentially enhancing recovery of Si and Mn. Despite these considerations, the ability to produce any metal at all from such fine waste is a positive result. The reduction efficiency for key metals (Cr, Fe, Mn) and the successful segregation of metal and slag suggest that scaling up is plausible, as discussed later.

These results confirm the feasibility of producing a complex FeCrMnSi ferroalloy using technogenic raw materials. This opens up new opportunities for waste recycling and enhances the metallurgical industry's raw material base.

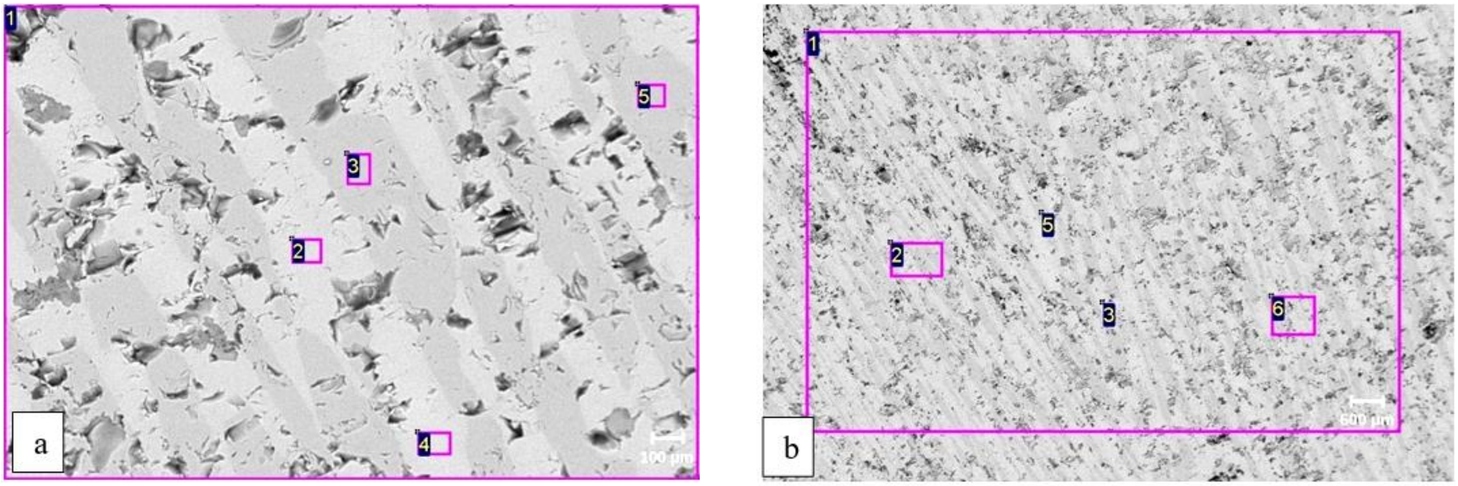


Fig. 4 SEM images of microstructure

The microstructure of the chromium-manganese-silicon ferroalloy sample was examined using scanning electron microscopy (SEM) (JEOL JXA8230), followed by energy-dispersive spectroscopy (EDS) analysis of the microstructural components. **Fig. 4** presents SEM images illustrating the alloy's microstructure.

Fig. 4 shows the formation of two primary phases distinguishable by color due to the backscattered electron detection mode. Energy-dispersive spectroscopy (EDS) analysis was performed on the points marked in Fig. 4, with the results summarized in **Table 3**.

Table 3 Results of EDS analysis (Figure 4)

Spectrum	Fig 4 a					Spectrum	Fig 4 b				
	Weight, %						Weight, %				
	Cr	Mn	Si	Fe	C		Cr	Mn	Si	Fe	C
1	56.7	7.3	4.3	19.0	12.8	1	54.1	7.3	4.6	20.0	14.0
2	44.6	9.6	8.7	29.8	7.3	2	58.6	6.8	4.1	18.5	12.0
3	74.0	4.7		8.5	12.9	3	37.8	10.5	7.2	31.4	13.1
4	39.2	11.1	9.0	34.2	6.4	5	71.6	4.4	0.1	8.1	15.7
5	74.0	4.7		8.3	12.9	6	55.6	7.4	4.9	20.7	11.4

The EDS results indicate an average composition of approximately 54–56% Cr, 7% Mn, 4% Si, 19–20% Fe, and 12–14% C. The average EDS values were calculated from multiple point measurements in different regions of the alloy sample, specifically spectrum No. 1 in Figure 4a and 4b. However, it is important to note that EDS provides a localized surface analysis and does not always fully represent the bulk composition. The discrepancies between the EDS results and the wet chemical analysis are likely due to the inhomogeneous distribution of phases within the alloy, particularly the presence of carbide (the darker phases) and silicide phases (brighter phases). Wet chemical analysis was also performed to obtain a more accurate overall composition, which is considered more representative of the bulk material. It is also important to note that the elevated carbon content observed in the EDS results is largely due to methodological factors inherent to the technique (EDS can detect elements down to boron (Z=5). Still, quantification of light elements like carbon by EDS is semi-quantitative at best). This explains the discrepancy with the analytical chemistry results, where the carbon content was measured at 4.53%.

Therefore, the EDS is used primarily to identify which phase was carbide-rich vs. silicide-rich, rather than to determine the exact bulk carbon content.

Comparing the EDS results with the backscattered electron images reveals two distinct silicon content and carbon concentration phases. Based on the elemental composition obtained from EDS analysis, the first phase is primarily composed of chromium carbides, likely Cr_3C_2. In contrast, the second phase consists of complex silicides, potentially $(Fe,Cr,Mn)_5Si_3$ or $(Fe,Cr,Mn)Si_2$. Such a microstructure is characteristic of complex ferroalloys containing Cr, Mn, and Si, where carbide and silicide phases form due to the thermodynamic stability of these compounds under the given smelting conditions [23].

It is worth noting that carbon reduction in the new FeCrMnSi ferroalloy can be achieved using standard decarbonization methods. This is also confirmed by the fact that the alloy's microstructure is similar to that of high-carbon ferrochrome, whose decarburization process is successfully used in industry [23].

As the traditional method for producing such ferroalloys involves smelting in electric arc furnaces, further research in this area, leveraging the data obtained in this study, is necessary.

CONCLUSION

A physicochemical analysis of technogenic waste-based charge materials was conducted to produce a chromium-manganese-silicon ferroalloy. Based on the analysis and thermodynamic modeling, smelting was performed at 1750 °C for 15 minutes. The highly dispersed charge materials—chromium dust, manganese dust, and coal slurry—were briquetted using 10–15% aqueous liquid glass solutions (10% of total mass), ensuring suitability for furnace use.

The resulting alloy had the following average composition (wt.%): Cr – 40.80; Mn – 19.44; Si – 9.75; Fe – 25.44; C – 4.53. Laboratory results confirmed the viability of using Cr and Mn dust as alternatives to expensive ores, enabling the production of FeCrMnSi ferroalloy from industrial waste.

Microstructural analysis and EDS revealed two main phases: one based on chromium carbide and another on complex silicide. These results support the potential for mass production of this complex alloy using waste, offering cost advantages and replacing more expensive ferroalloys with equivalent Cr, Mn, and Si content.

This process resembles one-step carbothermic smelting but uses waste instead of natural ores. Key reduction reactions (Cr_2O_3, MnO, SiO_2 by C) remain unchanged, allowing application of classical methods (e.g., Kazachkov's) with adaptations for higher gangue content. This makes waste-based smelting compatible with existing infrastructure.

Due to its Si and Mn content, FeCrMnSi is primarily suited for steel deoxidation. While Cr is typically used for alloying, in this case, it contributes to deoxidation and refining. The high carbon content may limit direct use in alloyed steels, but standard decarburization methods (e.g., vacuum refining, oxidative treatment) can reduce carbon levels, as done for high-carbon ferrochrome.

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