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RESEARCH PAPER

Production of manganese-bearing ligatures from iron–manganese ore beneficiation tailings by ore-thermal smelting

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ABSTRACT

Amid the depletion of high-grade manganese raw materials, the utilization of low-grade ores and beneficiation tailings has become an important direction for expanding the raw-material base of ferroalloy production. This study evaluated the feasibility of producing manganese ligatures from high-silica ferromanganese ore beneficiation tailings of the Ushkatyn III and Tur deposits. The study assessed the technological suitability of these technogenic materials for producing non-standard manganese-bearing ligatures intended for steel alloying. Experimental smelting was conducted in a 200 kVA ore-thermal electric furnace. Material balances were established, and the chemical and phase compositions of the resulting products were determined. The smelting of Ushkatyn III tailings produced a high-carbon ferromanganese-type ligature containing 40–55% Mn and 4–6% C. Manganese recovery into the metallic phase was 56.4–77.6% for the Ushkatyn III tailings and 74.3–82.5% for the Tur tailings. In contrast, the processing of Tur tailings resulted in a silicomanganese-type ligature containing 45–50% Mn and 17–22% Si. The resulting ligatures may be considered as alloying additions for structural, reinforcing, and tool steels, provided that their carbon, silicon, and phosphorus contents are taken into account. The findings demonstrate the potential of ferromanganese ore beneficiation tailings as an alternative raw material for producing manganese-bearing ligatures with controlled chemical compositions.

Keywords: manganese ligature; ferromanganese ore; beneficiation tailings; ore-smelting process; low-grade raw materials; phase analysis

INTRODUCTION

Modern metallurgy is increasingly affected by the gradual depletion of high-grade mineral resources and the increasing complexity of the available raw-material base. This problem is particularly important for ferroalloy production, where the chemical and mineralogical quality of the ore feed determines the consumption of reductants, fluxes, electrical energy, and the stability of the smelting process. The decreasing availability of high-grade and readily beneficiated ores, together with the limited replenishment of the raw-material base, necessitates the incorporation of low-grade ores, substandard mineral products, and technogenic materials into metallurgical processing [1]. For Kazakhstan, this issue is especially relevant because manganese mining and processing are associated not only with natural mineral deposits but also with accumulated beneficiation products and tailings that have not yet been fully utilized on an industrial scale [2].

Manganese is one of the most important alloying elements for the steel industry. It is used as a deoxidizing, desulfurizing, and alloying component and contributes to the production of steels with improved strength, hardness, toughness, and wear resistance. In 2023, global manganese ore production was about 20 million tons in terms of manganese content, with the largest production volumes concentrated in South Africa, Gabon, and Australia [3]. Kazakhstan also possesses manganese-bearing raw materials; however, a significant part of the available reserves and processed materials consists of low-grade, high-silica, and iron-manganese ores, which do not always satisfy the requirements for standard manganese ferroalloy production [4]. The strategic importance of manganese is also confirmed by its inclusion in modern raw-material information systems and criticality assessments, where it is considered an essential material for steelmaking and emerging industrial sectors [5].

Commercial manganese ferroalloys, including high-carbon ferromanganese and silicomanganese, are mainly produced in submerged arc furnaces using manganese ore, carbonaceous reductants, and fluxing materials. The technological efficiency of this process depends on the manganese grade, Mn/Fe ratio, silica content, reducibility of manganese oxides, slag basicity, carbon reactivity, and furnace electrical conditions [6, 7]. Recent reviews of manganese alloy production emphasize that raw-material quality, reductant type, slag composition, furnace temperature, and energy consumption remain the key factors controlling both metal recovery and environmental performance of submerged arc furnace smelting [8, 9]. In Kazakhstan, studies on silicomanganese smelting have also shown that the use of manganese agglomerates and non-standard manganese-bearing materials requires careful control of charge composition and smelting conditions [10].

The processing of low-grade manganese and ferromanganese ores is technologically difficult because manganese may occur in oxide, silicate, carbonate, and mixed iron-manganese phases. In such ores, valuable manganese minerals are frequently associated with quartz, calcite, aluminosilicates, hematite, and other gangue or iron-bearing phases. This mineralogical complexity reduces the efficiency of conventional beneficiation methods and often leads to manganese losses in tailings [11]. Magnetic separation can be effective for some siliceous manganese ores, but its efficiency decreases for ferruginous ores where manganese and iron minerals have complex textural relationships and similar separation behavior [12]. Studies on refractory ferromanganese ores of Kazakhstan have also confirmed that gravity and magnetic beneficiation can produce concentrates with limited suitability for direct ferroalloy smelting, which indicates the need for combined or alternative processing routes [13].

Different approaches have been proposed to improve the beneficiation and metallurgical preparation of manganese-containing materials. These include magnetization roasting followed by magnetic separation, flotation, microwave-assisted treatment, hydrometallurgical processing, and chemical activation methods [14-17]. However, such methods are not always economically justified for low-grade materials with moderate manganese content, high silica content, and a considerable proportion of fine fractions. Repeated beneficiation, agglomeration, or hydrometallurgical processing may require additional energy, reagents, equipment, and environmental-control measures. Therefore, direct high-temperature processing in ore-thermal furnaces may be a more practical option for some manganese-bearing tailings, particularly when the objective is to obtain non-standard manganese-bearing ligatures rather than conventional high-grade ferroalloys.

The use of mining and beneficiation wastes as secondary raw materials is consistent with the principles of resource efficiency and circular economy in the mining and metallurgical sector. Mine tailings are increasingly considered not only as environmental liabilities but also as potential sources of valuable metals and mineral components [18, 19]. Their processing can reduce the volume of accumulated waste, decrease the need for primary ore extraction, and provide additional feedstock for metallurgical production. Techno-economic studies on tailings valorization have shown that the feasibility of such processing depends on the content of valuable components, technological complexity, capital costs, and the possibility of obtaining marketable products [20].

For manganese-containing technogenic materials, this direction is of particular interest because large volumes of fine, substandard, and high-silica materials are formed during mining, crushing, screening, and beneficiation operations. Recent studies have shown that manganese sludge and tailings can be converted into metallurgical feedstock by beneficiation and agglomeration, producing concentrates or pellets suitable for subsequent ferroalloy production [21]. Other works have demonstrated the possibility of obtaining ferroalloys from manganese-containing dusts and other technogenic products by electric smelting in ore-thermal furnace conditions [22]. Similar approaches to processing non-standard mineral and technogenic raw materials have also been applied to produce complex ferroalloys, confirming the practical relevance of direct pyrometallurgical treatment of challenging feedstocks [23].

In this context, beneficiation tailings of high-silica ferromanganese ores from the Ushkatyn III and Tur deposits are of practical interest. These materials contain manganese in quantities sufficient for metallurgical use but are not fully utilized because of their non-standard composition, high silica content, and variable mineralogical characteristics. The Ushkatyn III tailings contain manganese-bearing oxide, silicate, and carbonate phases, together with iron-bearing minerals, whereas the Tur tailings are characterized by a high silica content and the predominance of manganese oxides and silicates. These features make conventional beneficiation difficult but potentially suitable for direct ore-thermal processing to produce non-standard manganese ligatures.

Previous studies have mainly focused on the beneficiation and agglomeration of manganese sludge and tailings [21], the electric smelting of manganese-containing dusts [22], and the production of complex ferroalloys from other non-standard raw materials [23]. However, published information on the direct ore-thermal smelting of untreated high-silica ferromanganese beneficiation tailings remains limited. In particular, the relationships among charge basicity, slag composition, manganese recovery, manganese losses, and the type of ligature formed have not been sufficiently investigated under pilot-scale furnace conditions.

The aim of the present study was to experimentally evaluate the feasibility of producing manganese and silicomanganese ligatures by direct ore-thermal smelting of ferromanganese ore beneficiation tailings from the Ushkatyn III and Tur deposits. The study focused on establishing material balances, characterizing the chemical and phase compositions of the resulting products, and assessing the technological applicability of the produced ligatures for alloying structural, reinforcing, and tool steels. The proposed approach is intended to expand the raw-material base of manganese ferroalloy production and contribute to the utilization of low-grade manganese-containing beneficiation tailings.

MATERIAL AND METHODS

The raw materials used to produce the manganese ligatures included beneficiation tailings from the Ushkatyn III and Tur deposits. As reductants for smelting, low-ash coal from the Shubarkol deposit and special coke were employed. Lime was used as a fluxing additive.

The raw materials and smelting products were characterized by chemical analysis, X-ray fluorescence spectrometry, and X-ray diffraction analysis. Experimental smelting was conducted in an ore-thermal electric furnace.

Chemical and X-ray fluorescence analyses were conducted at the Zh. Abishev Chemical-Metallurgical Institute by specialists of the Testing Center. The chemical composition of the samples was determined using a vacuum wavelength-dispersive X-ray fluorescence spectrometer, Spectroscan MAX-GVM (manufactured by NPO «Spectron», Saint Petersburg, Russia). The spectrometer operates on the principle of irradiating the sample with X-rays, measuring the intensity of the secondary fluorescent radiation at specific wavelengths, and determining the elemental concentrations based on pre-established calibration curves.

X-ray diffraction analysis of the raw materials and smelting products was performed using an Empyrean diffractometer (Malvern Panalytical) at Abylkas Saginov Karaganda Technical University. The measurements were conducted at room temperature using Cu Kα radiation ($K\alpha_1$ = 1.541874 Å) over a 2θ range of 0–100°, with a step size of 0.013°.

Phase identification and semi-quantitative analysis were performed using Match! version 4 by comparing the experimental diffraction patterns with reference diffraction data.

Experimental studies on the production of manganese ligatures were conducted in a 200 kVA ore-thermal furnace. The 200 kVA furnace provided pilot-scale smelting conditions that reproduced the principal technological features of ore-thermal processing. The design and operating principles of the furnace unit located at the pilot plant of the Zh. Abishev Chemical and Metallurgical Institute are described in detail in Ref. [23].

RESULTS AND DISCUSSION

Study of raw material characteristics

Ushkatyn III beneficiation tailings. The feasibility of using Ushkatyn III ferromanganese ore beneficiation tailings as a raw material for producing a non-standard high-carbon manganese-bearing ligature was investigated. The average chemical composition of the tailings is presented in Table 1.

Table 1 Average chemical composition of beneficiation tailings from the Ushkatyn III deposit

Chemical composition, %						
Mn_{total}	Fe_{total}	SiO_2	Al_2O_3	MgO	CaO	S/P
24.1	11.2	48.7	2.6	1.4	4.9	0.27/0.029

The chemical composition indicates that the tailings can be processed directly without additional beneficiation, agglomeration, or iron-removal stages. This approach simplifies the process flowsheet and reduces the number of preliminary processing operations.

The phase composition of the Ushkatyn III tailings, determined by XRD analysis, is presented in Figure 1 and Table 2.

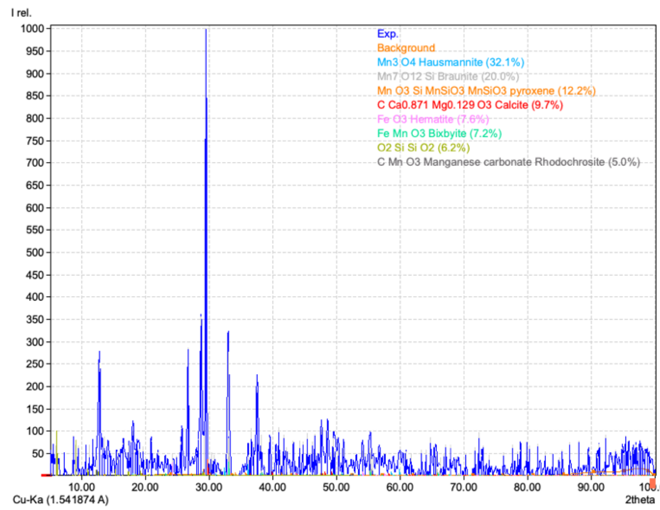

Fig. 1 X-ray diffraction pattern of ferromanganese ore beneficiation tailings from the Ushkatyn III deposit

Table 2 Phase composition of Ushkatyn III beneficiation tailings

Name of mineral	Formula	Content, %
Hausmannite	Mn_3O_4	32.1
Braunite	$Mn_7O_{12}Si$	20.0
Rhodonite	MnSiO3	12.2
Calcite	$CaCO_3$	9.7
Hematite	Fe_2O_3	7.6
Bixbyite	$(Mn, Fe)_2O_3$	7.2
Quartz	SiO_2	6.2
Rhodochrosite	$MnCO_3$	5.0

XRD analysis showed that the Ushkatyn III tailings had a complex multiphase composition dominated by manganese oxides and silicates. Hausmannite (Mn_3O_4) was the predominant manganese-bearing phase, accounting for 32.1%. The substantial contents of braunite ($Mn_7O_{12}Si$) and rhodonite ($MnSiO_3$) indicated that a considerable proportion of manganese occurred in silicate phases. The carbonate phases were represented by calcite ($CaCO_3$) and rhodochrosite ($MnCO_3$). Hematite (Fe_2O_3) and bixbyite ($(Mn,Fe)_2O_3$), a manganese–iron oxide solid solution, were identified as iron-bearing phases. Quartz (SiO_2) was also detected. This multiphase composition influences the reduction behavior of the tailings during ore-thermal smelting.

Tur beneficiation tailings. The average chemical composition of the Tur beneficiation tailings is presented in Table 3. Their phase composition, determined by XRD analysis, is shown in Figure 2 and Table 4.

Table 3 Average chemical composition of beneficiation tailings from the Tur deposit

Chemical composition, %						
Mn_{total}	Fe_{total}	SiO_2	Al_2O_3	MgO	CaO	S/P
21.2	11.91	44.7	6.5	1.2	1.4	0.025/0.034

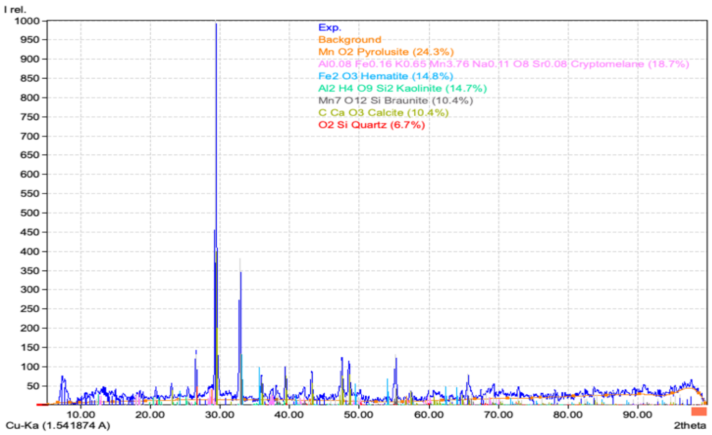

Fig. 2 X-ray diffraction pattern of ferromanganese ore beneficiation tailings from the Tur deposit

Table 4 Results of X-ray phase analysis of ferromanganese ore tailings from the Tur deposit

Name of mineral	Formula	Content, %
Pyrolusite	MnO_2	24.3
Cryptomelane	KMn_8O_{16}	18.7
Hematite	Fe_2O_3	14.8
Kaolinite	$Al_2[Si_2O_5](OH)_4$	14.7
Braunite	$Mn_7O_{12}Si$	10.4
Calcite	$CaCO_3$	10.4
Quartz	SiO_2	6.7

X-ray phase analysis of manganese ore beneficiation tailings from the Tur deposit showed that the mineral composition is represented mainly by oxide forms of manganese, among which pyrolusite (MnO_2) and cryptomelane (KMn_8O_{16}) were identified. The presence of hematite (Fe_2O_3) and kaolinite ($Al_2[Si_2O_5](OH)_{4)}$ was also established, indicating the presence of iron-containing and aluminosilicate phases. Braunite ($Mn_7O_{12}Si$), calcite ($CaCO_3$) and quartz (SiO_2) were identified in the tailings as associated minerals. The complex mineral composition with a predominance of manganese oxides and impurities of silicate and carbonate compounds determines the specifics of the subsequent processing of this raw material.

Reductants. Low-ash Shubarkol coal and special coke were selected as reductants for smelting the manganese-bearing ligatures. Their proximate analyses and ash compositions are presented in Tables 5 and 6, respectively.

Table 5 Technical and ash composition of Shubarkol coal used as a reducing agent

Material	Content, %									
	Technical composition				Chemical composition of ash					
	C_{solid}	A	V	W	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	P_2O_5
Shubarkol coal	50.4	2.9	42.0	9.0	57.09	22.19	2.68	2.56	7.11	0.54

Shubarkol coal contained 42.0% volatile matter and only 2.9% ash. Its high volatile-matter content promoted rapid heating and reduction, whereas its low ash content limited the introduction of additional slag-forming components. The coal ash consisted mainly of SiO_2 and Al_2O_3, which contributed to the overall slag composition.

Table 6 Technical and ash composition of special coke used as a reducing agent

Material	Content, %									
	Technical composition				Chemical composition of ash					
	C_{solid}	A	V	W	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	P_2O_5
Special coke	86.8	5.8	4.3	10.6	60.91	22.31	2.68	4.70	7.53	0.133

Special coke contained 86.8% fixed carbon and relatively low amounts of volatile matter and ash, making it suitable for high-temperature reduction. Its ash is composed mainly of SiO_2 and Al_2O_3 and also contains MgO and Fe_2O_3, which contribute to the overall slag composition.
The selected reductants provided the required reducing capacity while limiting the introduction of excessive slag-forming components, thereby contributing to stable furnace operation and the formation of the target ligatures.

Results of large-scale laboratory studies

Material balances for the ore-thermal smelting of the Ushkatyn III and Tur beneficiation tailings are presented in Tables 7 and 8, respectively.

Table 7 Material balance of ore-thermal smelting using Ushkatyn III tailings

Given:	kg	%	Received:	kg	%
Coal part: - Special coke - Shubarkol coal	 10.2 11.7	 6.4 7.4	Alloy	34.0	21.4
Tailings of Ushkatyn III ore	100	63	Slag	90.0	56.7
Lime	36.8	23.2	Gas and dust losses	34.7	21.9
Total	158.7	100		158.7	100

Table 8 Material balance of ore-thermal smelting using Tur tailings

Given:	kg	%	Received:	kg	%
Coal part: - Special coke - Shubarkol coal	 16.1 18.7	 11.2 13.0	Alloy	35	24.3
Tailings of Tur ore	100	69.4	Slag	74	51.4
Lime	9.2	6.4	Gas and dust losses	35	24.3
Total	144	100		144	100

The material balances were calculated per 100 kg of beneficiation tailings for a target alloy manganese content above 40%. The combined share of slag and gas/dust products was 78.6% for the Ushkatyn III charge and 75.7% for the Tur charge, reflecting the high gangue content of the investigated tailings. The corresponding alloy yields were 21.4% and 24.3%, respectively, and can be considered satisfactory for low-grade high-silica manganese-bearing raw materials.
The lime dosage was varied to control slag basicity in accordance with the target alloy composition. A higher lime addition was used for the Ushkatyn III charge to limit silica reduction and silicon transfer into the metal, whereas a lower lime addition for the Tur charge promoted the formation of a silicomanganese-type ligature.
The charge materials were crushed, sized, and homogenized before smelting. After the furnace bath had been heated and conditioned for 12 h, the first batch of the charge mixture was loaded around the electrode, and the burden level gradually increased. This loading procedure ensured uniform filling of the furnace bath without abrupt fluctuations in the electrical load. Additional portions of the charge were introduced as the burden level subsided. The metal was tapped periodically, weighed, and sampled for chemical analysis.

Fig. 3 Tapping of manganese ligature from the ore-thermal furnace during pilot-scale experiments

The average chemical compositions of the ligatures and slags obtained from the two types of tailings are presented in Tables 9 and 10.

Table 9 Chemical composition of the high-carbon ferromanganese ligature and slag obtained from Ushkatyn III beneficiation tailings

Content, %						
Metal						
Mn	C	Si	P	S	Fe	Mn recovery
40–55	4–6	3–7	0.1–0.15	≤ 0.02	balance	56.4–77.6
Slag						
CaO	SiO_2	Al_2O_3	MnO	MgO	Fe_{total}	B*
38–42	43–47	2.5–4.0	7–13	1–2	≤ 2	0.85–1.00
*Notation: Slag basicity was calculated as $B=(CaO+MgO)/SiO_2$						

Table 10 Chemical composition of the silicomanganese ligature and slag obtained from Tur beneficiation tailings

Content, %						
Metal						
Mn	C	Si	P	S	Fe	Mn recovery
45–50	1–2	17–22	0.1–0.15	≤ 0.02	balance	74.3–82.5
Slag						
CaO	SiO_2	Al_2O_3	MnO	MgO	Fe_{total}	B*
18–21	52–56	11–14	8–13	2–3	≤ 3	0.35–0.42
*Notation: Slag basicity was calculated as $B=(CaO+MgO)/SiO_2$						

The chemical compositions of the obtained products indicate the formation of two different types of manganese-bearing ligatures. Smelting of the Ushkatyn III tailings favored the production of high-carbon ferromanganese-type ligature, whereas the processing of the Tur tailings resulted in a silicomanganese-type product. This difference was primarily associated with the behavior of silica during reduction and its transfer into the metallic phase.

The phosphorus content of the obtained ligatures should be considered when selecting their steelmaking application. Assuming complete phosphorus transfer and the addition of sufficient ligature to introduce 1% Mn into the steel, the calculated increase in the phosphorus content of the steel is approximately 0.0018–0.0038%, depending on the ligature composition. Therefore, the ligatures may be used for conventional steel grades provided that the initial phosphorus content of the melt and the specified phosphorus limit of the target steel grade are taken into account. Their use for low-phosphorus and high-purity steels requires a separate phosphorus balance.

The estimated manganese recovery into the metallic phase was 56.4–77.6% for the Ushkatyn III tailings and 74.3–82.5% for the Tur tailings. The higher recovery observed for the Tur tailings indicates a more complete transfer of manganese into the silicomanganese ligature under the applied smelting conditions.

The slag compositions were consistent with the target alloy compositions. The higher lime addition during the processing of the Ushkatyn III tailings increased slag basicity, reduced silica activity, and limited silicon reduction. In contrast, the lower lime addition in the Tur charge maintained a more acidic, silica-rich slag and promoted silicon transfer into the alloy. The residual MnO content indicated incomplete manganese reduction, whereas the low total iron content showed that most of the iron had been transferred to the metallic phase.

To quantitatively assess the transfer of manganese to the slag, manganese losses were estimated from the slag yield and MnO content relative to the amount of manganese introduced with the initial tailings using the following equation:

$$L_{Mn} = \frac{m_{slag} \cdot w(MnO) \cdot 0.774}{m_{tailings} \cdot w(Mn)} \cdot 100,$$

where m_{slag} is the slag mass, kg; $w(MnO)$ is the MnO content in slag, %; $m_{tailings}$ is the mass of original tailings, kg; $w(Mn)$ is the manganese content in original tailings, %; 0.774 is the mass fraction of Mn in MnO.

The estimated manganese losses with slag were 20.2–37.6% for the Ushkatyn III tailings and 21.6–35.1% for the Tur tailings. The comparable loss ranges indicate incomplete manganese reduction in both smelting processes. These losses were mainly associated with the high slag yield and the residual MnO content in the silica-rich slags.

Previous investigations of manganese-containing technogenic materials have generally involved preliminary beneficiation or agglomeration before ferroalloy production [21], or have focused on manganese-bearing dusts and other types of non-standard raw materials [22, 23]. In contrast, the present study demonstrates the direct smelting of untreated high-silica beneficiation tailings. The results further show that adjustment of the lime dosage and slag basicity provides a means of controlling silicon transfer and, consequently, the type of manganese-bearing ligature formed. The simultaneous evaluation of alloy yield, manganese recovery, residual MnO in the slag, and manganese losses provides a more complete assessment of the technological feasibility of this processing route.

The resulting ligatures were further examined by XRD to determine their phase compositions. The corresponding diffraction patterns and phase compositions are presented in Figures 4 and 5 and Tables 11 and 12, respectively.

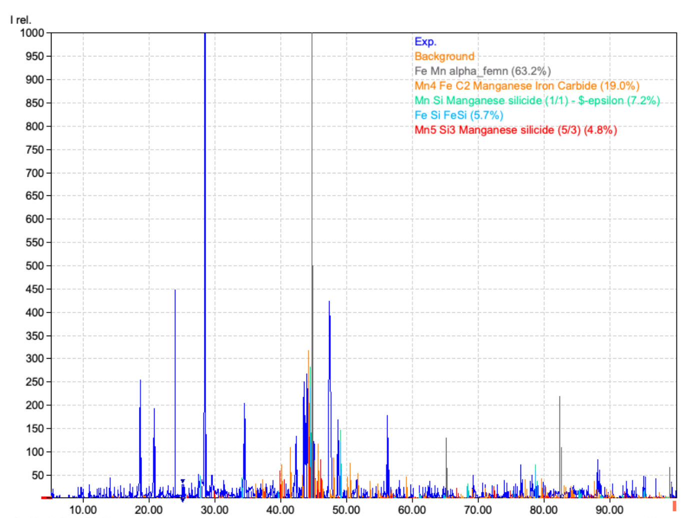

Fig. 4 X-ray diffraction pattern of high-carbon ferromanganese ligature produced from Ushkatyn III tailings

Table 11 Phase composition of high-carbon ferromanganese ligature (Ushkatyn III)

Formula/ phase	Content, %
FeMn (α-femn)	63.2
Mn_4FeC_2	19.0
MnSi	7.2
FeSi	5.7
Mn_5Si_3	4.8

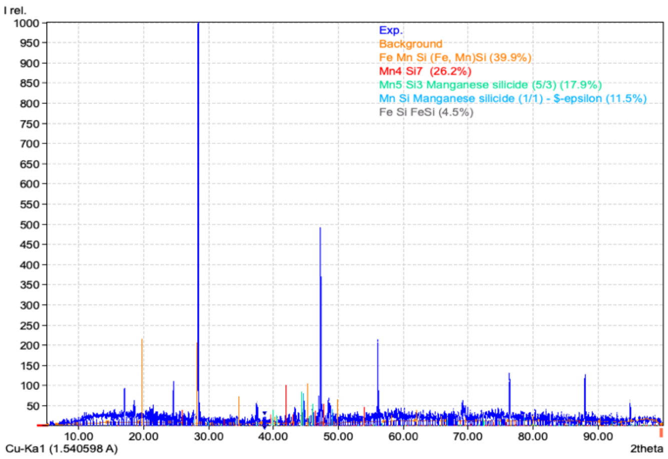

Fig. 5 X-ray diffraction pattern of silicomanganese ligature produced from Tur tailings

Table 12 Phase composition of silicomanganese ligature (Tur)

Formula/ phase	Content, %
(Fe, Mn) Si	39.9
Mn_4Si7	26.2
Mn_5Si_3	17.9
MnSi	11.5
FeSi	4.5

XRD analysis revealed distinct phase assemblages in the ligatures produced from the two types of tailings. Ferromanganese and carbide phases were predominant in the ligature obtained from the Ushkatyn III tailings. This phase assemblage was consistent with carbothermic reduction followed by the formation of manganese- and iron-containing carbides. The moderate proportion of silicide phases indicated that silica reduction contributed to alloy formation to a limited extent.

In contrast, the ligature produced from the Tur tailings was dominated by manganese and iron silicides. The prevalence of these phases indicated more extensive silicon transfer into the metallic phase and confirmed that silica reduction played a greater role in the formation of the Tur-derived ligature.

The differences in the phase compositions of the ligatures resulted from both the characteristics of the initial tailings and the applied smelting conditions, particularly the slag basicity and the extent of silica reduction. These findings demonstrate that the phase composition and chemical characteristics of the final ligature can be controlled through the selection of the charge composition and smelting regime. The pilot-scale smelting tests confirmed the technological feasibility of producing manganese-bearing ligatures directly from the Ushkatyn III and Tur beneficiation tailings without preliminary beneficiation. Despite the relatively low manganese content of the initial materials, non-standard ligatures containing 40–55% Mn were obtained. Their chemical compositions and phase assemblages were consistent with ferromanganese-type and silicomanganese-type products, depending on the feed composition and slag conditions.

CONCLUSION

Pilot-scale smelting of the Ushkatyn III beneficiation tailings produced a high-carbon ferromanganese-type ligature containing 40–55% Mn, 4–6% C, and 3–7% Si. The obtained ligature may be considered an alloying addition for carbon and low-alloy steels such as 20G2 (0.18–0.26% C and 1.3–1.6% Mn), 30G2 (0.26–0.35% C and 1.4–1.8% Mn), and 20GS (0.17–0.22% C, 1.0–1.5% Mn, and 1.0–1.5% Si), as well as for carbon tool steels such as U8 and U10, containing approximately 0.75–0.84% and 0.95–1.04% C, respectively.

Smelting of the Tur beneficiation tailings produced a silicomanganese-type ligature containing 45–50% Mn and 17–22% Si. This ligature may be considered an alloying addition for low-alloy structural steels such as 09G2S (up to 0.12% C, 1.3–1.7% Mn, and 0.5–0.8% Si) and 10G2S1 (up to 0.12% C, 1.3–1.65% Mn, and 0.8–1.1% Si), as well as for corrosion-resistant chromium–nickel steels such as 12Kh18N10T (up to 0.12% C, 17–19% Cr, 9–11% Ni, and 0.4–1.0% Ti) and 12Kh18N9 (up to 0.12% C, 17–19% Cr, and 8–10% Ni).

The applicability of the obtained ligatures to specific steel grades should be assessed with consideration of the initial phosphorus content of the melt and the permissible phosphorus limit of the target steel grade.

The manganese recovery into the metallic phase was 56.4–77.6% for the Ushkatyn III tailings and 74.3–82.5% for the Tur tailings. The differences in the resulting alloy compositions were governed by slag chemistry: a higher basicity of 0.85–1.00 limited silica reduction and favored the formation of a ferromanganese-type ligature, whereas a lower basicity of 0.35–0.42 promoted silicon transfer into the metallic phase and the formation of a silicomanganese-type ligature. Manganese losses with slag were estimated at 20.2–37.6% and 21.6–35.1%, respectively, indicating that further optimization of the reduction conditions may improve manganese recovery.

Additionally, both ligatures may be considered alloying additions for high-carbon manganese steels used in the production of grinding media, including grades 65G (approximately 0.62–0.70% C and 0.90–1.20% Mn) and 70G (approximately 0.67–0.75% C and 0.90–1.20% Mn).

The produced ligatures may partially replace standard manganese ferroalloys in selected steelmaking applications, provided that their manganese, silicon, carbon, and phosphorus contents are taken into account in the charge calculation. The use of beneficiation tailings as the principal manganese-bearing feedstock may reduce the consumption of primary ore and contribute to the utilization of accumulated technogenic materials.

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