IMPROVING THE TECHNOLOGY FOR EXTRACTING ZINC COMPOUNDS FROM STEEL SMELTING DUST

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Abstract

This study examines the efficacy of hydrogen in reducing iron compounds found in dust emissions during the electric arc furnace (EAF) steelmaking processes at "Uzbeksteel" JSC (Uzbekistan). EAF dust is a fine secondary material composed of 30 to 60 percent iron oxides (Fe_2O_3, Fe_3O_4, FeO). The accumulation of approximately 60,000 tons of this dust underscores the importance of developing sustainable recycling methods. The current investigation involved hydrogen reduction experiments conducted at 1100°C for 30 minutes, utilizing a continuous low-pressure hydrogen flow. Thermodynamic analysis using Ellingham diagrams indicated that iron oxides are selectively reduced between 650 and 750°C, where the standard free energy (ΔG) values are negative. However, the reduction of ZnO is only favorable at temperatures above 900°C. The reduction process is characterized by gas-solid interactions, the diffusion of hydrogen through porous particles, and the sequential transition of Fe_2O_3 to Fe_3O_4 to FeO to Fe. The experimental results demonstrate the metallization of iron and the partial volatilization of zinc, which facilitates the process. Furthermore, hydrogen promotes CO_2 free processing, enhancing environmental performance. Hydrogen has been shown to enable processing without carbon dioxide emissions, making it environmentally superior to carbon-based reductants.

Keywords: electric arc furnace dust, hydrogen reduction, iron oxides, zinc oxide, JSC “Uzbeksteel”, sustainable metallurgy, technogenic waste

1. INTRODUCTION

In the global metallurgical industry, steel production is a key sector of strategic importance. The sustainable development of the construction, mechanical engineering, transport, energy, mining, defense, and infrastructure sectors is directly dependent on the quality and volume of steel products. In recent years, the share of electric arc furnaces (EAF) in global steel production has been increasing. The main reasons for this are that EAF technology enables the use of secondary metal resources by re-melting scrap metal, its greater flexibility compared to the blast furnace-converter route, and its lower requirement for carbon-based inputs. According to the World Steel Association, the steel industry is responsible for approximately 7-9% of global CO_2 emissions, which makes recycling and the implementation of low-carbon technologies in this sector a pressing issue [1].

"Uzmetkombinat" JSC holds a leading position in the ferrous metallurgy industry of Uzbekistan. The company primarily produces high-quality steel products by melting various types of iron-containing scrap metal in electric arc furnaces. In this process, the composition of the charge is of critical importance, as galvanized steel products, brass and bronze parts, cable sheaths, paint, and other coating materials within the scrap cause

components such as Zn, Pb, Cd, Cr, Cl, and F to transfer into the dust during smelting. As a result, dust is generated during the steel smelting process, which is then captured by gas purification systems. EAF dust is finely dispersed, has a complex mineralogical composition, and is enriched with heavy metals, making it both an environmentally hazardous waste and a valuable secondary raw material. Scientific literature indicates that EAF dust typically contains 25-50% Fe and 5-40% Zn, as well as Pb, Cd, Cr, Mn, Na, K, Cl, and other trace elements [4, 10].

The hazardous nature of steelmaking dust is attributed to the presence of heavy metal compounds in its composition. Specifically, compounds of zinc, lead, cadmium, and chromium pose an ecological threat should they seep into the soil and groundwater. For this reason, EAF dust is classified as hazardous industrial waste in many countries. However, viewing this dust merely as waste is incorrect, as it contains iron oxides, zinc oxide, zinc ferrite, and other valuable components. Therefore, processing EAF dust holds a twofold significance: firstly, it mitigates ecological risks; and secondly, it enables the reintroduction of valuable components like iron and zinc into the production chain. This approach is fully consistent with the concepts of a circular economy and resource-efficient metallurgy [2, 3].

This problem is particularly acute in the case of "Uzmetkombinat" JSC. It is noted that up to 60,000 tons of steel-smelting dust have accumulated in the company's warehouses, and up to 10,000 tons of new dust containing as much as 17% ZnO is generated annually. Returning this dust directly to the steel-smelting furnace is complicated, as volatile components like zinc and lead re-vaporize in the furnace and re-enter the gas purification system. This creates a "circulating load," increases the amount of dust, negatively affects the furnace's operating mode, and places an additional load on the gas purification units. Therefore, it is considered more effective not to add the dust directly to the charge, but rather to separate zinc, lead, and other volatile components from it and redirect the iron-rich residue back into the metallurgical process [6, 10].

To date, various technologies have been proposed for processing EAF dust, including pyrometallurgical, hydrometallurgical, combined pyrometallurgical-hydrometallurgical, chlorination, vacuum reduction, microwave heating, the use of biochar and biomass, and hydrogen reduction methods. One of the traditional industrial methods is the Waelz process, in which the dust is treated with a carbonaceous reducing agent at a high temperature, zinc is separated in a vapor state, and subsequently condensed as ZnO. While this process is widely used in industry, its limitations include high energy consumption, CO_2 emissions, additional slag formation, and in some cases, issues related to lead, chlorine, and alkali metals. Although Małecki et al. have shown that high efficiency can be achieved in extracting metals from EAF dust, the generation of large volumes of secondary slag from the Waelz process has also been highlighted as a separate problem [10, 11, 26].

Hydrometallurgical methods, particularly selective leaching techniques using acidic, alkaline, and complex-forming solvents, are a significant approach for extracting zinc from EAF dust. Dutra et al. investigated the possibilities of selective zinc leaching in an alkaline medium, and subsequent studies have demonstrated the decomposition of zinc ferrite and enhanced zinc extraction through hydrothermal reduction in a NaOH system. Nevertheless, the high chemical stability of the $ZnFe_2O_4$ phase, the necessity of solution purification, reagent consumption, and the neutralization of waste solutions remain significant technological obstacles in hydrometallurgical processes. Recent studies have proposed schemes utilizing ionic liquids, organic acids, ultrasound-assisted leaching, and combined thermal-leaching processes; however, their economic viability on an industrial scale has not always been sufficiently substantiated [5, 9, 12, 15, 24, 25].

One of the primary scientific challenges in processing EAF dust is determining the mineral phases in which zinc is located. Zinc in the dust is most often found as ZnO and $ZnFe_2O_4$. While ZnO can be relatively easily reduced or dissolved, the $ZnFe_2O_4$ or franklinite phase possesses high thermodynamic stability, which complicates zinc extraction. Wu et al. studied the reduction behavior of zinc ferrite and demonstrated that the decomposition of this phase is a key step in the effective processing of EAF dust. Meanwhile, Ma et al. determined that the process of zinc reduction and extraction consists of several kinetic stages: initially, the

reduction of $ZnFe_2O_4$ and ZnO; followed by the reduction of ZnO and iron oxides; and in the final stage, the diffusion of gaseous products determines the rate of the process [7, 13].

In recent years, chlorination and oxygen-assisted chlorination methods have also gained significant attention. Huang et al. investigated the possibility of separating zinc from ZnFe2O4 in the presence of $MgCl_2$, showing that oxygen-assisted chlorination can transfer zinc into a volatile phase as $ZnCl_2$ with high selectivity. In a 2024 study, this approach was applied to EAF dust, where it was noted that the zinc chlorination rate could exceed 97%, while iron chlorination could remain below 1%. These results are important for the selective separation of zinc and iron. However, handling chlorine-based reagents, the risk of corrosion, gas purification, and managing chlorinated waste require specific engineering solutions for the industrial implementation of such processes [17-19].

Microwave heating, vacuum carbothermic reduction, and biomass-based reduction technologies are also among the promising directions for processing EAF dust. For example, microwave heating can enhance the volatility of zinc by accelerating the internal heating of the dust particles. Wang et al. (2025) studied the effects of temperature, holding time, and the C/Zn molar ratio on zinc separation during the microwave carbothermic reduction process. Huo et al. demonstrated that a high degree of zinc extraction is achievable by reducing EAF dust with a CO/H_2 mixture generated from biomass gasification. These approaches may be more environmentally advantageous than traditional carbon reduction, but issues of process stability, gas composition control, and industrial-scale implementation require further research [14, 16, 20, 23].

In the context of decarbonizing the metallurgical industry, the hydrogen reduction process is gaining particular importance. Unlike carbon-based reducing agents, hydrogen produces water vapor during the reduction process, rather than CO or CO_2. For this reason, it is considered a low-carbon technological solution for the reduction of iron oxides, zinc oxide, and zinc ferrite. According to IEA data, the iron and steel sector requires significant technological changes to reduce CO_2 emissions, and hydrogen-based processes are regarded as one of the key directions in this transformation [2]. The advantage of hydrogen reduction for EAF dust is that it simultaneously allows for the transfer of zinc to the gas phase and the reduction of iron oxides to their metallic or low-valence state. As a result, zinc can be separated as a Zn or ZnO product, while the iron-rich residue can be returned to the steelmaking process [21, 22, 28].

Studies published up to 2025 have shown that temperature and gas composition play a crucial role in the hydrogen-based reduction of EAF dust. Leuchtenmüller et al. emphasize that precise temperature control in the range of 900–1200 °C is necessary for zinc separation and the reduction of iron phases. Khaidarov et al. proposed a combined scheme of carbothermic and H_2 reduction, noting that it can mitigate the costs and supply constraints of using only hydrogen while also lowering the high CO_2 emissions associated with carbon-based reduction [21, 22]. The hydrogen fluidized-bed roasting method proposed by Zhu et al. demonstrates that the process rate can be increased by improving gas-solid phase contact during the processing of zinc-bearing dusts [29].

From this perspective, scientific research on processing the zinc-containing steelmaking dust generated at "Uzmetkombinat" JSC is highly relevant. The problem at hand encompasses several areas: first, an in-depth study of the chemical and mineralogical composition of the dust; second, determining whether zinc is present in ZnO, $ZnFe_2O_4$, or other phases; third, investigating the phase transformations of zinc and iron under hydrogen or combined reduction conditions; and fourth, assessing the feasibility of returning the resulting iron-rich residue to the steelmaking process. This approach serves to neutralize waste, expand the raw material base, extract zinc from secondary sources, and implement the principles of a circular economy in steel production [27, 30].

Therefore, the issue of processing zinc-bearing steelmaking dust is not merely an environmental problem, but also a strategic scientific and technical task directly linked to the comprehensive use of resources, the creation of import-substituting raw material sources, and the low-carbon development of the metallurgical industry. A

review of the literature indicates that while traditional carbothermic methods for processing EAF dust have been industrially proven, they are limited by high energy consumption and CO_2 emissions. Hydrometallurgical methods are promising in terms of selectivity, but face challenges with the stability of the zinc ferrite ($ZnFe_2O_4$) phase and the purification of solutions. Although chlorination and microwave reduction demonstrate high efficiency, they require additional solutions for industrial safety and technological stability. Hydrogen reduction, however, represents an environmentally friendly and promising direction for separating zinc and returning iron to the metallurgical cycle, which necessitates the development of a scientifically-based technology for the comprehensive processing of accumulated EAF dust under the specific conditions of Uzbekistan [20–23, 28–30].

2. MATERIALS

A dust sample generated during the steelmaking process at "Uzmetkombinat" JSC was selected as the object of study. This dust is a fine-particle, man-made product carried away with the gases emitted during the melting of a scrap-based charge in electric arc furnaces and is captured by gas cleaning systems. Along with iron oxides, steelmaking dust contains oxide compounds of zinc, lead, manganese, silicon, calcium, aluminum, sodium, and other elements. Consequently, it is considered both an environmentally hazardous waste and a valuable secondary raw material. Therefore, the primary scientific and practical objective of this study was defined as the reduction of iron oxides to metallic iron by treating this dust with hydrogen, and the evaluation of the behavior of the zinc compounds.

The steelmaking dust obtained for the study consists mainly of micron-sized particles, and their high dispersity creates favorable conditions for gas-solid phase reactions with hydrogen (**Figure 1**). Due to the large specific surface area of the fine particles, hydrogen molecules can actively contact the oxide phases. Furthermore, the porous structure of the dust particles facilitates the penetration of gas into the inner layers. However, at high temperatures, the process rate can be limited by particle sintering, pore closure, and increased diffusion resistance. Therefore, technological parameters such as temperature, time, hydrogen flow, and sample mass were considered as important factors in this study.

Figure 1. A sample of steelmaking dust prepared for hydrogen reduction

The general composition of steelmaking dust typically consists of iron oxides such as Fe_2O_3, Fe_3O_4, and FeO; zinc oxide in the form of ZnO; as well as other supplementary oxides like CaO, SiO_2, MgO, Al_2O_3, and PbO. The proportion of these components varies depending on the charge composition, the temperature regime of the smelting process, the share of galvanized scrap, the efficiency of the gas cleaning system, and the technological condition of the steelmaking unit. Specifically, galvanized scrap, brass and bronze parts, cable sheaths, and metal fragments with protective coatings lead to an increase in Zn and Pb compounds within the

dust. This circumstance necessitates studying the dust not merely as simple iron-containing waste, but as a complex metallurgical technogenic raw material.

The chemical composition of the sample used in the study was characterized by the following components: Fe_{tot} - 31.2%, Fe_2O_3 - 41.6%, FeO - 4.6%, P_2O_5 - 0.2%, SO_3 - 0.9%, SiO_2 - 3.4%, ZnO - 16.2%, PbO - 1.36%, CuO - 0.36%, C - 2.4%, CaO - 3.4%, Al_2O_3 - 0.9%, MnO - 3.7%, Cr_2O_3 - 0.6%, NiO - 0.03%, TiO_2 - 0.14%, and Na_2O - 10.4%. These results indicate that iron oxides are the primary component of the dust, with zinc oxide present as a significant secondary valuable component. The total iron content of 31.2% confirms the potential for obtaining an iron-rich product by reducing the dust. A ZnO content of 16.2% makes it crucial to address the transfer of zinc to the gas phase or its extraction as a separate product.

Table 1 Chemical composition of steelmaking dust from “Uzbeksteel” JSC

Element / Compound	**Fe_{tot}**	**Fe_2O_3**	**FeO**	**P_2O_5**	**SO_3**	**SiO_2**	**ZnO**	**PbO**	**CuO**	**C**	**CaO**	**Al_2O_3**	**MnO**	**Cr_2O_3**	**NiO**	**TiO_2**	**Na_2O**
Content, %	31.2	41.6	4.6	0.2	0.9	3.4	16.2	1.36	0.36	2.4	3.4	0.9	3.7	0.6	0.03	0.14	10.4

As shown in **Table 1**, the amounts of Fe_2O_3 and FeO in the dust determine the primary pathway of the hydrogen reduction process. Fe_2O_3, a high-valence iron oxide, is sequentially reduced by hydrogen through the stages of Fe_3O_4, FeO, and finally Fe. FeO, in turn, is the final oxide phase before the formation of metallic iron. The high concentration of ZnO in the dust increases the probability of zinc separating during the process, either as volatile compounds or as metal vapor. Concurrently, components such as CaO and SiO_2 can form silicate compounds at high temperatures, while Na_2O can influence the emergence of phases with low melting points. This has a significant impact on the process kinetics, the degree of sintering, and the phase composition of the final product.

Before conducting the experiment, the dust sample underwent a preparation stage. First, the sample was dried to remove its free moisture content. This step is necessary to minimize unexpected evaporation, moisture-induced particle agglomeration, and inaccuracies in mass change measurements during the hydrogen reduction process. Following this, the sample was mixed and homogenized. Homogenization is crucial for ensuring the reproducibility of the experiment, as steelmaking dust can be heterogeneous in its chemical and granulometric composition. A100 g sample was taken from the prepared dust and placed in a laboratory furnace for the hydrogen reduction experiments.

Hydrogen reduction experiments were conducted in a high-temperature laboratory furnace. For the study, the primary experimental parameters were a 100 g sample, a heating temperature of 1100 °C, and a holding time of 30 minutes. During the process, hydrogen was continuously supplied at a low pressure. A continuous flow of hydrogen is necessary to maintain a stable reducing atmosphere in the reaction zone, remove the resulting water vapor, and prevent the re-oxidation of the metallic iron. Hydrogen consumption can be determined during the experiments based on the process temperature, sample mass, gas flow rate, and degree of reduction. Optimizing hydrogen consumption in subsequent stages is important for evaluating the reduction efficiency and economic indicators.

The hydrogen reduction process is a complex, gas-solid phase heterogeneous reaction that consists of several consecutive stages. In the first stage, hydrogen molecules are carried by a gas stream to the surface of the dust particles. In the second stage, H_2 molecules are adsorbed on the particle surface and diffuse into the inner layers through the porous structure. In the third stage, hydrogen reacts with iron oxides, reducing them to lower-valence oxides and metallic iron. In the fourth stage, the H_2O vapor formed as a result of the reaction diffuses from the interior of the particle to the external environment and is carried out of the reaction zone by the gas flow. Therefore, the rate of the process depends not only on the chemical reaction rate but also on the external and internal diffusion of the gas.

The reduction of iron oxides with hydrogen proceeds in the following sequence:

$$Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe \quad (1)$$

In this sequence, the hematite phase is first reduced to magnetite, then magnetite to wüstite, and finally wüstite to metallic iron. The main reactions of the process are expressed as follows:

$$3Fe_2O_3 + H_2 \rightarrow 2Fe_3O_4 + H_2O \quad (2)$$

$$Fe_3O4 + H_2 \rightarrow 3FeO + H_2O \quad (3)$$

$$FeO + H_2 \rightarrow Fe + H_2O \quad (4)$$

In general, the reduction of hematite to metallic iron is expressed by the following equation:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (5)$$

In these reactions, hydrogen acts as a reducing gas, causing oxygen to be separated from the iron oxides and removed from the system as water vapor. A high H_2/H_2O ratio is important for the reduction process to proceed thoroughly. If the amount of water vapor in the reaction zone increases, the equilibrium may shift to the left, and the degree of reduction may decrease. Therefore, the continuity of the hydrogen flow and the timely removal of product gases are among the important factors determining the efficiency of the process.

According to the results of a thermodynamic evaluation, the reduction of iron oxides by hydrogen can occur even at relatively low temperatures. An analysis of the ΔG–T diagrams shows (**Table 2**) that the reduction of Fe_2O_3 to Fe_3O_4 becomes thermodynamically favorable at temperatures above 350 °C, the reduction of Fe_3O_4 to FeO at temperatures above 450 °C, and the reduction of FeO to metallic iron at temperatures above 550–600 °C.

Table 2 Selection of Temperature Range Based on ΔG–T Diagrams

Reaction	Temperature range where ΔG < 0
$Fe_2O_3 \rightarrow Fe_3O_4$	≥ 350 °C
$Fe_3O_4 \rightarrow FeO$	≥ 450 °C
$FeO \rightarrow Fe$	≥ 550–600 °C

Based on these data, the temperature range of 650–750 °C was identified as the thermodynamically optimal initial interval for the hydrogen reduction of iron oxides. In this range, the Gibbs free energy for the reactions has a negative value, indicating that the reducing potential of hydrogen is sufficient. However, in actual steelmaking dust, the process is not limited to the reduction of iron oxides alone. Due to the presence of components in the dust such as ZnO, potentially $ZnFe_2O_4$, PbO, MnO, CaO, SiO_2, and Na_2O, phenomena like interphase interactions, sintering, the formation of low-melting-point compounds, and internal diffusion limitations occur. For this reason, a temperature of 1100 °C was selected for the practical experiment. This high temperature allows for increasing the volatility of zinc compounds, accelerating the decomposition of complex oxide phases, and evaluating the formation of an iron-rich reduced product.

During the process, particular attention was given to the behavior of zinc oxide. In a hydrogen environment, ZnO can be reduced at high temperatures and transition into the gas phase as either metallic zinc vapor or re-oxidized ZnO. Because the boiling point of zinc is relatively low, its volatility increases in a high-temperature reducing environment. Therefore, a temperature of 1100 °C can create favorable conditions for separating zinc from the iron-rich residue. However, the complete separation of zinc depends not only on the temperature but also on the hydrogen flow, reaction duration, particle size, and whether the ZnO is located in a separate phase or within the zinc ferrite structure.

The study employs a method of comparing the composition of the initial dust and the processed product to evaluate the reduction efficiency. The main evaluation criteria adopted are the degree of iron reduction, the decrease in the amounts of Fe_2O_3 and FeO, the increase in the amount of metallic iron, the decrease in the amount of ZnO, the degree of zinc's transition into the gas phase, and the suitability of the residual product for

metallurgical reprocessing. Furthermore, it is also necessary to assess the accumulation of Zn and Pb compounds in the condensate or dust-collection products formed as a result of the process.

It is recommended to use X-ray phase analysis to determine the phase composition of the sample, X-ray fluorescence or atomic emission analysis for its chemical composition, scanning electron microscopy to evaluate microstructural changes, and energy-dispersive analysis to determine elemental distribution. These analyses allow for an in-depth assessment of the conversion of iron oxides into metallic iron, the decomposition of zinc compounds, the formation of silicate phases, and changes in particle morphology during the hydrogen reduction process.

Thus, the research methodology is aimed at determining the feasibility of processing the steelmaking dust from "Uzbeksteel" JSC using hydrogen. This methodology includes the stages of studying the chemical composition of the dust, preparing samples, carrying out the hydrogen reduction process at high temperatures, evaluating the thermodynamic principles, and analyzing the composition of the processed product. The chosen approach serves to scientifically substantiate the possibilities for the complex extraction of iron and zinc from steelmaking dust, reducing the amount of environmentally hazardous waste, and returning the iron-rich product to the steelmaking process.

3. RESULTS

The The results of the process for reducing steelmaking dust with hydrogen show that this method is a promising approach for processing complex technogenic raw materials containing iron and zinc compounds. In the study, a dust sample generated during the steelmaking process at "Uzmetkombinat" JSC was processed at high temperatures in a hydrogen environment. The reduction of iron oxides to metallic iron and the transition of zinc oxide to the gas phase were evaluated. The obtained results indicated that the thermodynamic and kinetic behavior of iron and zinc compounds differ during the hydrogen reduction process. This specific difference creates the potential for the selective separation of iron and zinc.

One of the significant advantages of hydrogen reduction is the possibility of a stepwise and relatively selective reduction of iron oxides compared to zinc oxide. Iron oxides are reduced by the action of hydrogen in the following sequence: $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$. In this process, hydrogen combines with oxygen to form water vapor. As a result, the oxygen within the iron oxides is removed, and metallic iron is formed. The overall process is expressed by the following reaction:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad (6)$$

Furthermore, in the final stage, the reduction of FeO to metallic iron occurs through the following reaction:

$$FeO + H_2 \rightarrow Fe + H_2O \quad (7)$$

These reactions are thermodynamically favorable in a hydrogen atmosphere, with the reduction of iron oxides proceeding most actively in the 650–750 °C temperature range. According to the analysis of Ellingham diagrams, the Gibbs free energy for the reduction of FeO to Fe is negative within this temperature range, which indicates that the reaction can proceed spontaneously. However, in practice, higher temperature regimes are also required due to the complex composition of the dust, the high dispersion of particles, and the presence of zinc ferrite and other complex oxide phases. Therefore, conducting the experiment at 1100 °C in this study is justified to increase the volatility of zinc compounds and to evaluate the possibility of obtaining an iron-rich reduced product.

During the hydrogen reduction process, the behavior of zinc oxide differs from that of iron oxides. Zinc oxide can be reduced by hydrogen through the following reaction:

$$ZnO + H_2 \rightarrow Zn + H_2O \quad (8)$$

However, for this reaction, $\Delta G < 0$ is observed mainly at high temperatures, specifically under conditions above approximately 900 °C. This means that in the range of 650–750 °C, the reduction of iron oxides to metallic iron

proceeds actively, while the reduction of ZnO to metallic zinc is limited. At higher temperatures, the reduction of ZnO and the transition of the resulting metallic zinc into a vapor state intensify. Since the boiling point of zinc is relatively low, at a temperature of 1100 °C, it can transition into the gas phase and then re-condense in colder zones. This situation creates favorable conditions for separating zinc from the iron-rich solid residue.

Figure 2 shows the sample obtained as a result of hydrogen reduction. Analysis of the image reveals that the appearance of the processed product has changed significantly compared to the initial dust. The sample's color changing to a darker metallic hue is explained by the reduction of iron oxides and the formation of a metallic iron phase. At the same time, the formation of a white-gray coating or deposit is observed in certain areas. This white-gray product may be attributed to ZnO formed by the re-oxidation or condensation of zinc vapors on colder surfaces, as well as finely dispersed oxide products formed in the presence of water vapor.

Figure 2 Sample obtained from hydrogen reduction

According to the experimental results, the majority of the zinc oxide compounds in the sample transitioned into a volatile state within a high-temperature hydrogen environment. This process can occur in two stages. In the first stage, ZnO is partially reduced by hydrogen, forming metallic zinc. In the second stage, the resulting zinc transitions into a vapor state under the influence of high temperature and is separated from the main solid residue by the gas stream. Subsequently, in zones with lower temperatures, the zinc vapor can either re-condense or re-oxidize into ZnO upon contact with an oxygen-containing environment. Therefore, the formation of white-gray products around the post-experiment sample or on the surface of the solid product is considered a natural occurrence.
This process can be represented by the following general sequence:

$$ZnO + H_2 \rightarrow Zn_{(g)} + H_2O \quad (9)$$

$$Zn_{(g)} + 1/2O_2 \rightarrow ZnO \quad (10)$$

The first reaction occurs in the high-temperature reducing zone. The second reaction, however, can occur as a result of cooling or contact of the gas phase with oxidizing components. Consequently, the zinc compounds are separated from the main solid iron-rich residue and accumulate as separately collected dust or condensate. This represents a significant technological advantage in the processing of steelmaking dusts.

The difference between the reduction of iron oxides and the volatility of zinc compounds forms the basis of the selective separation process. In the 650–750 °C range, the FeO → Fe reaction proceeds actively, while ZnO is not fully reduced. This stage is favorable for converting iron oxides into a metallic phase. At temperatures

above 900 °C, the reduction of ZnO by hydrogen and the subsequent evaporation of the resulting zinc intensify. Therefore, by organizing the process in stages, it is possible to first reduce the iron oxides and then transfer the zinc to the gas phase at a higher temperature. This approach increases the efficiency of the selective separation of iron and zinc.

The water vapor generated during the experiment also has a significant effect on the process kinetics. Hydrogen removes oxygen from the iron and zinc oxides, forming H_2O. If the resulting water vapor is not promptly removed from the reaction zone, the equilibrium of the reduction reactions may shift to the left. This, in turn, slows the complete reduction of the iron oxides. For this reason, a continuous supply of hydrogen and the removal of H_2O vapor via the gas stream are crucial conditions for process efficiency. A continuous flow of low-pressure hydrogen maintains a stable reducing environment, minimizing the probability of re-oxidation.

In hydrogen reduction, particle size and the porous structure of the dust are also of significant importance. Because steelmaking dust consists of micron-sized particles, hydrogen molecules come into rapid contact with the particle surface. This increases the chemical reaction rate. However, at high temperatures, adhesion and sintering processes can occur between the particles. Sintering reduces porosity, hinders hydrogen's penetration into the inner layers, and slows the release of H_2O vapor. Therefore, although a temperature of 1100 °C is beneficial for zinc vaporization, it is necessary to optimize the temperature-time regime for the deep reduction of iron oxides and the preservation of the product's porosity.

A thermodynamic analysis of the results reveals that the reducing capacity of hydrogen in the Fe–O–H and Zn–O–H systems varies depending on the temperature. While the reduction of iron oxides is favorable even at relatively low temperatures, the reduction of zinc oxide requires a high temperature. Therefore, the result observed in the experiment—the concentration of iron in the solid residue and the transition of zinc to a vapor state—is consistent with thermodynamic principles. This circumstance allows the hydrogen reduction process to be evaluated as a promising method for the comprehensive processing of steelmaking dust.

Based on the research findings, it was determined that three primary technological outcomes can be achieved during the hydrogen reduction process. First, iron oxides are reduced to metallic iron, forming an iron-rich solid product. Second, zinc oxide is reduced and vaporized at high temperatures, separating it from the main solid product. Third, the resulting zinc vapors can be collected as a zinc product through separate cooling and condensation. This approach allows steelmaking dust to be processed not as simple waste, but as a secondary raw material containing iron and zinc.

The discussion results indicate that the hydrogen reduction process also offers significant environmental advantages. While traditional carbon-based reduction methods produce CO and CO2 gases, the primary gaseous product in hydrogen reduction is water vapor. This reduces the process's carbon footprint. Concurrently, the ability to control the separation of zinc, lead, and other volatile compounds from the dust mitigates the environmental risk of industrial waste. The iron-rich residue can be redirected back into the steelmaking process, which improves raw material efficiency.

Thus, the obtained results indicate that hydrogen reduction technology can be an effective scientific and practical solution for processing steelmaking dust from "Uzbeksteel" JSC. During the process, iron oxides are reduced to metallic iron, while zinc oxide transitions to a vapor state at high temperatures and separates from the main solid residue. A thermodynamic assessment based on Ellingham diagrams confirms that the FeO → Fe reaction proceeds actively in the 650–750 °C range, whereas the ZnO → Zn reaction is favored at temperatures above 900 °C. This substantiates the possibility of selectively separating iron and zinc. In the future, to further enhance the process efficiency, it is necessary to conduct in-depth studies on hydrogen consumption, temperature, holding time, particle size, gas flow rate, and the conditions for zinc vapor condensation.

4. CONCLUSION

Research has shown that the hydrogen reduction technology for dust generated during the steelmaking process at JSC "Uzbeksteel" is an effective, environmentally safe, and promising method for the comprehensive processing of iron- and zinc-bearing industrial waste. Steelmaking dust contains iron oxides, zinc oxide, lead oxide, and other oxide compounds; storing this dust in landfills as ordinary waste poses an environmental risk. At the same time, the iron and zinc compounds within this dust allow it to be processed as a valuable secondary raw material.

An analysis of the chemical composition of the steelmaking dust, selected as the object of study, revealed the following content: total iron (Fe_{tot}) at 31.2%, Fe_2O_3 at 41.6%, FeO at 4.6%, and ZnO at 16.2%. This provides a basis for classifying the dust as a technogenic raw material containing both iron and zinc. The high dispersion and porous structure of the dust create favorable kinetic conditions for gas-solid phase reactions with hydrogen. This structure accelerates the transport of hydrogen molecules to the particle surface, their diffusion into the inner layers, and their reaction with the oxide phases.

The hydrogen reduction process is characterized by the sequential reduction of iron oxides. The process proceeds through the stages $Fe_2O_3 \rightarrow Fe_3O_4 \rightarrow FeO \rightarrow Fe$. In this process, hydrogen combines with oxygen to form water vapor. The removal of the resulting H_2O vapor from the reaction zone is a crucial factor for the deep and stable progression of the reduction process. If water vapor accumulates in the reaction zone, the equilibrium of the reduction reactions can shift in the reverse direction, and the rate of metallic iron formation may decrease. Therefore, the continuous supply of hydrogen and the stable maintenance of the gaseous environment are among the primary conditions that determine the efficiency of the process.

The results of the thermodynamic analysis showed that the reduction of iron oxides by hydrogen can occur even at relatively low temperatures. According to Ellingham diagrams, the reduction of Fe_2O_3 to Fe_3O_4, Fe_3O_4 to FeO, and FeO to metallic iron becomes thermodynamically favorable at temperatures above 350 °C, 450 °C, and 550–600 °C, respectively. Based on this, the 650–750 °C range can be considered the optimal temperature interval for the reduction of iron oxides. However, the reduction and vaporization of zinc oxide require higher temperatures. For the $ZnO + H_2 \rightarrow Zn + H_2O$ reaction, $\Delta G < 0$ is observed primarily at temperatures above 900 °C. Therefore, in high-temperature regimes, the selective separation of zinc from the iron-rich residue becomes possible through its transition to a vapor state and subsequent condensation.

The research findings demonstrated that during the hydrogen reduction process, iron oxides can be reduced to metallic iron, while zinc oxide can transition to a volatile state at high temperatures. This allows for the concentration of iron in the solid product and the collection of zinc as a separate condensate or a secondary zinc-containing product. Consequently, processing steelmaking dust reduces environmental risks on one hand, and on the other, creates an additional source of raw materials for the metallurgical industry.

Another significant advantage of hydrogen reduction technology is its environmental friendliness. While traditional carbon reduction processes generate CO and CO_2 gases, the primary gaseous product in hydrogen reduction is water vapor. This reduces the process's carbon footprint and aligns with the requirements of modern low-carbon metallurgy. At the same time, this creates an opportunity to establish a waste-free or low-waste technological scheme by returning the iron-rich recycled product to the steelmaking process and separating the zinc-rich product.

Overall, the technology for hydrogen reduction of steelmaking dust is a promising scientific and practical solution for processing the dust accumulated at "Uzbeksteel" JSC, extracting iron and zinc components, reducing environmental risks, and making efficient use of raw material resources. For future industrial-scale implementation, it is necessary to conduct in-depth research on hydrogen consumption, temperature, holding time, gas flow rate, particle size, zinc vapor condensation conditions, and the feasibility of reusing the recycled product in the steelmaking process.

REFERENCES

[1] World Steel Association. World Steel in Figures 2024. Brussels: World Steel Association, 2024.

[2] International Energy Agency. Iron and Steel. IEA, 2024–2025.

[3] OECD. Unlocking Potential in the Global Scrap Steel Market. OECD Publishing, 2024.

[4] Lanzerstorfer, C. "Electric Arc Furnace Dust: Application of Air Classification." Journal of Cleaner Production, 2018.

[5] Dutra, A.J.B., Paiva, P.R.P., Tavares, L.M. "Alkaline Leaching of Zinc from Electric Arc Furnace Steel Dust." Minerals Engineering, 2006.

[6] Pickles, C.A. "Thermodynamic Analysis of the Selective Carbothermic Reduction of Electric Arc Furnace Dust." Journal of Hazardous Materials, 2008.

[7] Wu, C.C., et al. "Reduction Behavior of Zinc Ferrite in EAF-Dust Recycling." Journal of Environmental Management, 2014.

[8] Chairaksa-Fujimoto, R., Inoue, Y., Umeda, N., Itoh, S., Nagasaka, T. "New Pyrometallurgical Process of EAF Dust Treatment with CaO Addition." International Journal of Minerals, Metallurgy and Materials, 2015.

[9] Chairaksa-Fujimoto, R., Maruyama, K., Miki, T., Nagasaka, T. "The Selective Alkaline Leaching of Zinc Oxide from Electric Arc Furnace Dust Pre-Treated with Calcium Oxide." Hydrometallurgy, 2016.

[10] Wang, J., Zhang, Y., Cui, K., Fu, T., Gao, J., Hussain, S., AlGarni, T.S. "Pyrometallurgical Recovery of Zinc and Valuable Metals from Electric Arc Furnace Dust — A Review." Journal of Cleaner Production, 2021.

[11] Małecki, S., et al. "High-Performance Method of Recovery of Metals from EAF Dust." Materials, 2021.

[12] Teimouri, S., et al. "A New Hydrometallurgical Process for Metal Extraction from Electric Arc Furnace Dust." Materials, 2022.

[13] Ma, S., et al. "Kinetic Analysis of Recovering Zinc from Electric Arc Furnace Dust." Minerals, 2022.

[14] Yang, J., et al. "Research for the Recovery of Zn and Pb from Electric Arc Furnace Dust by Vacuum Carbothermal Reduction." Journal of Materials Research and Technology, 2023.

[15] Zhang, D., Ling, H., Yang, T., Liu, W., Chen, L. "Selective Leaching of Zinc from Electric Arc Furnace Dust by a Hydrothermal Reduction Method in a Sodium Hydroxide System." Journal of Cleaner Production, 2019.

[16] Ye, Q., Peng, Z., Li, G., Lee, J., Liu, Y., Liu, M., Wang, L., Rao, M., Zhang, Y., Jiang, T. "Microwave-Assisted Reduction of Electric Arc Furnace Dust with Biochar." ACS Sustainable Chemistry & Engineering, 2019.

[17] Huang, J., et al. "Chlorination of $ZnFe_2O_4$ by Molten $MgCl_2$: Effect of Adding Oxygen." Journal of Sustainable Metallurgy, 2023.

[18] Huang, J., et al. "Oxygen-Assisted Zinc Recovery from Electric Arc Furnace Dust Using Magnesium Chloride." International Journal of Minerals, Metallurgy and Materials, 2024.

[19] Hamann, C., et al. "Selective Removal of Zinc and Lead from Electric Arc Furnace Dust by Chlorination and Thermal Treatment." Journal of Hazardous Materials, 2024.

[20] Huo, X., et al. "Efficient Reduction of Electric Arc Furnace Dust by CO/H_2 Derived from Biomass Gasification." Waste Management, 2025.

[21] Leuchtenmüller, M., et al. "Impact of Temperature and Gas Composition on Hydrogen-Based Direct Reduction of Electric Arc Furnace Dust." International Journal of Hydrogen Energy, 2025.

[22] Khaidarov, T.B., et al. "An Innovative Approach Toward Enhancing the Recovery of Fe and Zn from Zinc-Bearing Electric Arc Furnace Dusts." Sustainability, 2025.

[23] Wang, K., et al. "Influencing Factors and Mechanisms of Zinc Recovery from Electric Arc Furnace Dust by Microwave-Assisted Carbothermic Reduction." Metals, 2025.

[24] Rudnik, E., et al. "Comparative Studies on Leachability of Zinc and Iron from Electric Arc Furnace Waste." Molecules, 2025.

[25] Rudnik, E., et al. "Hydrometallurgical Treatment of EAF By-Products for Metal Recovery." Metals, 2025.

[26] Grudinsky, P., et al. "The Waelz Slag from Electric Arc Furnace Dust Processing." Materials, 2024.

[27] Koishina, G., et al. "Technology for Producing Pure Lead-Free Zinc Oxide from Electric Arc Furnace Dust." Vestnik Satbayev University, 2025.

[28] Liu, Y., Li, H., Jin, L., Liu, S. "Towards Low-Carbon Zinc Extraction from Zinc-Containing Electric Arc Furnace Dust: A Review of Pyrometallurgical and Hydrometallurgical Routes." Journal of Environmental Chemical Engineering, 2026.

[29] Zhu, X., et al. "Hydrogen Fluidization Roasting Process to Treat Zinc-Bearing Dust." Minerals Engineering, 2026.

[30] Yang, H., et al. "Resource Utilization of Electric Arc Furnace Dust: Efficient SO2 Purification and Zinc Recovery." Journal of Environmental Management, 2025.