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Research Article

Feasibility Study on the Recovery of Iron Nuggets from Steelmaking By-products

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ABSTRACT

Steelmaking by-products have increasingly drawn attention due to their large volumes, stockpiling, and associated environmental concerns. In Iran, the electric arc furnace (EAF) steelmaking process relies heavily on direct-reduced iron (DRI) as its primary feedstock. The by-products generated, including sludge, mill scale, and dust, generally contain only small amounts of valuable non-ferrous metals. Therefore, the primary focus of recycling efforts is the efficient recovery of iron to maximize resource utilization and enhance the sustainability of the steelmaking process. Direct reduction has emerged as a viable pathway for extracting iron from such materials as metallic iron nuggets or secondary DRI. This study evaluates the technical feasibility of recovering iron from three representative by-products (sludge, mill scale, and EAF dust) collected from a domestic steel plant. Experiments were conducted by reduction at 1450°C for 40 min, using a 50wt% reductant, under varying conditions of pellet composition, reductant type, particle size, and lime addition as a flux. The optimal performance was achieved with composite pellets consisting of equal proportions of the three by-products, 10wt% lime, and coarse graphite reductant (< 3mm). Under these conditions, 62.4wt% of the sample was converted into metallic iron nuggets with a metallization degree above 99%.

1. Introduction

Iron and steel plants worldwide generate significant amounts of by-products each year, and their effective management is critical from both environmental and economic perspectives. In the direct reduction–electric arc furnace (DRI–EAF) route, the principal by-products include sludge, EAF dust, EAF slag, and mill scale. Some by-products (e.g., EAF slag from DRI charging) are more complex and thus stockpiled until suitable processing technologies become available. In contrast, less complex residues, such as mill scale, can be recycled and reused more readily. Stockpiling of steelmaking by-products leads to environmental issues, including dust emissions, and requires considerable land for disposal [1–5].

Sludge generally refers to fine-grained by-products carried by water streams and collected as slurry. DRI sludge forms gas scrubbing in Midrex shaft furnaces and is primarily composed of pellet fines and fine DRI particles, making it suitable for recycling in pelletizing plants [6]. In 2016, Tenova introduced a commercial DRI briquetting technology that compacts various fines and sludges into briquettes with a metallization degree

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of approximately 94–95% and ~3% carbon. These briquettes are charged directly into shaft furnaces, as pellets are. The first industrial unit was commissioned at Ternium's DRI plant in Mexico to recycle screening fines and DRI sludge [6]. Due to its magnetite-rich composition, sludge may also serve as an alternative iron-oxide source for other applications [7].

According to the World Steel Association, EAF steelmaking typically generates 15–20kg of dust per ton of crude steel [8]. In Iran, the figure is somewhat higher due to extensive DRI use. Global studies report 10–25 kg t^{-1} depending on feed and operating conditions [9]. The composition of EAF dust varies widely: DRI-based charges yield fine, low-density iron-oxide dust, while galvanized scrap increases Zn content. Various Zn-recovery methods are employed, including the Waelz kiln, RHF, OxyCup, and DK, with Waelz being the most commonly used [10]. New approaches, such as vacuum-carbothermic and plasma RHF processes, enable simultaneous Zn volatilization and Fe recovery [11, 12]. Due to the low Zn content in Iranian DRI, the emphasis should shift to iron recovery and recycling, in line with recent circular-economy roadmaps [13].

Mill scale—formed as the surface oxide during the casting and rolling of steel—accounts for about 1% of crude steel, occasionally reaching 1.5% depending on plant design [14]. It has been recycled through sintering and blast-furnace charging and tested for molten-steel temperature control and carbon removal [15]. Recent work explores its direct-reduction reuse and value-added applications, including magnetic adsorbent production [16] and sinter blend optimization [17].

Among the most promising technologies for valorizing steelmaking by-products, thermal processes based on complete reduction are particularly effective. These processes offer efficient iron recovery and sustainable management of materials such as sludge, mill scale, EAF slag, and EAF dust. In the RHF route, for example, dust, reductant, and flux are pelletized, dried, and charged in one to three layers on the hearth; reduction at 1250–1450°C for 10–20min produces metallic iron nuggets [9]. Given anticipated growth in Iranian steel production, these technologies should be rapidly developed to manage a portion of the by-product stream. The current study investigates the feasibility of producing metallic iron nuggets from three representative by-products—sludge, mill scale, and EAF dust—generated in a large domestic steel plant. The focus is on the effects of mineralogy and chemistry, reductant type and particle size, and flux addition on nugget formation and iron recovery.

2. Materials and Experimental Procedure

Representative samples of sludge (code S), EAF dust (code D), and mill scale (code M) were collected from the steelmaking line of a domestic plant. Initial characterization was conducted using chemical analysis, X-ray diffraction (XRD), and X-ray fluorescence (XRF) to comprehensively evaluate the composition and phase structure of the steelmaking by-products.

The experiments comprised grinding, pelletizing, and high-temperature reduction in a laboratory furnace (LHT 01/16, Nabertherm). Fig. 1. illustrates the experimental procedure. The main variables were the by-product type and blend composition, the reductant type, the particle size, and the amount of lime added as flux. The chemical compositions of the by-products and the properties of the two reductants (coke and graphite) are detailed in Tables 1 and 2., respectively.

Table 1. Composition of by-product and blended samples.

Sample code	Composition ratio (%)			FeT (%)	FeO (%)	FeM (%)
	Dust	Sludge	Mill scale			
D	100	–	–	16.8	0.1	0.33
S	–	100	–	61.0	43.1	11.7
M	–	–	100	72.3	37.7	17.7
MIX1	33.3	50.0	16.7	50.8	18.2	4.7
MIX2	33.3	33.3	33.3	50.0	22.0	5.2
MIX3	50.0	50.0	–	39.0	17.0	6.0
MIX4	25.0	25.0	50.0	73.3	16.5	4.0

Table 2. Properties of reductants.

Reductant	Fixed carbon (%)	Ash (%)	Volatiles (%)	Moisture (%)
Graphite	95.2	1.6	0.4	0.2
Coke	91.6	9.6	3.1	0.2

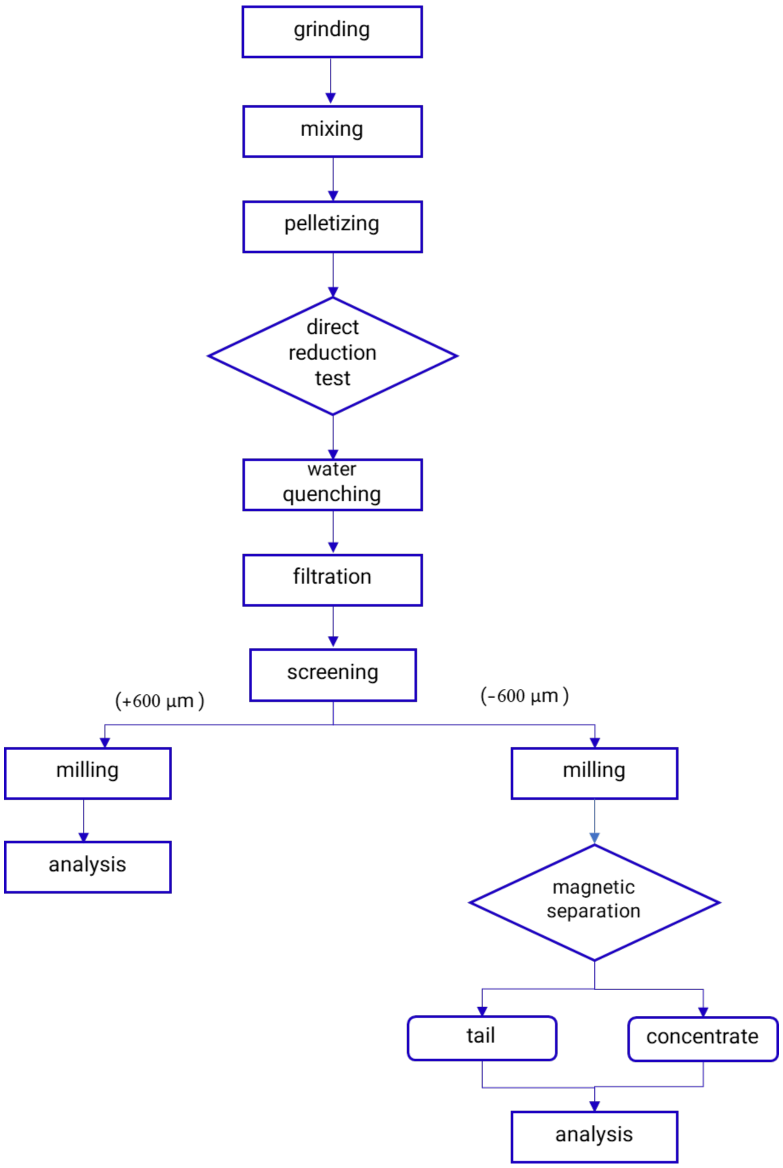

Fig. 1. Schematic of the experimental procedure.

The constant experimental conditions for the reduction tests included a reduction temperature of 1450°C, a holding time of 40min, and the addition of 50wt% reductant within the pellets. The products were water-quenched after the reduction process. Magnetic separation was performed at a field strength of 1000 Gauss. Pellets were prepared with 2wt% bentonite binder. The reference test used fine graphite as reductant without any flux addition.

3. Results and Discussion

3.1. Characterization

The total iron contents (FeT) of the three by-products were 16.8% for EAF dust (D), 61.0% for sludge (S), and 72.3% for mill scale (M) (Table 3.). XRD patterns (Fig. 2.) indicated that mill scale consisted mainly of iron oxides—hematite, magnetite, and wustite. The sludge sample revealed a phase composition comparable to that of iron-ore pellets and DRI (hematite, magnetite, wustite, and metallic iron). EAF dust was dominated by light particles and alkaline constituents such as lime, calcite, and periclase, with a few weak hematite peaks.

3.2. Reduction

Tests were performed under the constant experimental conditions outlined in Section 2. After the reduction process, the samples were quenched in water, dried, weighed, ground, and then subjected to magnetic separation at 1000 Gauss, yielding concentrate and tailings fractions. The chemical analyses of both fractions are summarized in Table 4.

Table 3. XRF analysis of by-product samples.

Sample	FeT (%)	SiO_2 (%)	Na_2O (%)	K_2O (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	TiO_2 (%)	MnO (%)	P_2O_5 (%)	SO_3 (%)	V_2O_5 (%)	L.O.I (%)
M	67.0	10.9	0.3	0.5	2.5	7.8	1.1	0.7	0.4	0.3	0.2	0.2	<0.1
S	60.0	11.8	0.4	0.5	4.2	7.9	0.5	0.7	0.5	0.3	0.2	0.3	1.3
D	17.0	25.8	2.4	0.4	9.9	14.9	3.9	0.4	1.5	1.5	1.5	1.7	16.7

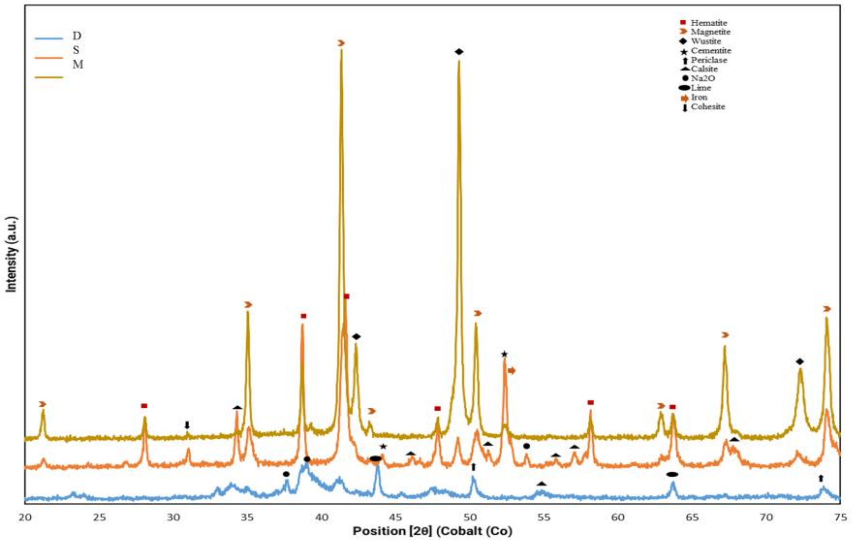

Fig. 2. XRD patterns of samples.

Table 4. Results of reduction tests on by-product samples.

Sample	Concentrate				Tailing		
	FeT (%)	FeO (%)	MD (%)	wt (%)	FeT (%)	FeO (%)	wt (%)
M	94.3	1.5	98.5	64.8	1.4	0.3	35.2
S	93.5	4.4	96.6	58.7	1.6	0.5	41.3
D	72.7	3.0	96.7	16.3	7.9	1.6	83.7

All magnetic concentrates exhibited metallization degrees above 95%, indicating that the reduction reactions proceeded almost to completion. Among the individual by-products, mill scale performed best, producing 64.8wt% magnetic concentrate with 94.3% total iron. The reduction of EAF dust resulted in the lowest metallic-iron recovery, yielding 16.3wt% concentrate with 72.7% total iron. The sludge sample showed intermediate performance, with 58.7wt% concentrate containing 93.5% total iron.

3.3. Reduction of Composite Samples

In continuation, composite pellets were prepared and reduced under the reference conditions. In the reduced products, coarse metallic iron particles were observed; therefore, an oversize fraction (>600µm) was separated by screening, and the undersize fraction was processed as illustrated in Fig. 1. Compositions of the composite samples (MIX1–MIX4) are presented in Table 1., and the reduction results are summarized in Table 5. MIX2 (an equally proportioned blend of the three by-products) achieved the highest metallic recovery, approximately 42.0wt%, producing coarse iron nuggets with >98% metallization. In comparison, MIX4 achieved 35wt% metallic fraction in the +600µm oversize, while MIX1 and MIX3 delivered 33.0wt% and 38wt%, respectively. The magnetic concentrates from all compositions exhibited metallization degrees >90%, consisting primarily of fine metallic iron particles that passed through the 600µm screen.

3.4. The Effect of Process Parameters

3.4.1. The Effect of Reductant Type and Particle Size

Given the favorable behavior of MIX2, the effects of reductant type (coke vs. graphite) and particle size (fine <100µm vs. coarse <3mm) were evaluated for this blend (Table 6.). Coarse graphite produced the highest fraction of oversize metallic iron (about 43.6wt% >1mm). The oversize fraction decreased to about 41.9wt% with fine graphite, approximately 39.4wt% with coarse coke, and about 29.5wt% with fine coke. The superior performance of coarse reductants is attributed to greater pellet porosity compared with pellets made with fine reductants. In contrast, fine particles offer a larger specific surface area and can block pores, limiting gas penetration. Previous studies likewise report that increasing reductant particle size enhances porosity, improves gas diffusion, and promotes formation of larger nuggets [18]. Graphite also outperformed coke, consistent with its lower ash and higher fixed carbon, resulting in higher metallization degrees in the products.

3.4.2. The Effect of Flux Addition

The influence of lime (CaO) addition as a flux was studied at 1450°C for 40min using coarse graphite as the reductant and the MIX2 composition (Table 7.). Increasing lime from 0 to 2, 5, and 10wt% raised the oversize metallic fraction from about 42.1 to 49.0, 51.3, and 62.4wt%, respectively. As a basic oxide, CaO promotes pellet swelling and cracking during reduction, thereby enhancing mass transfer and improving reducibility [19]. Based on these results, the optimal conditions for the materials investigated are: 1450°C, 40min, 50wt% coarse graphite (<3mm), 10wt% lime, and composite pellets with equal proportions of sludge, mill scale, and EAF dust.

Table 5. Results of reduction tests on composite samples.

Sample	Feed	Oversize (metallic)			Undersize (to magnetic separation)				
					Concentrate			Tailing	
	FeT (%)	FeT (%)	wt (%)	MD (%)	FeT (%)	wt (%)	MD (%)	FeT (%)	wt (%)
MIX1	40.79	81.5	33.0	97.1	67.0	14.0	87.7	2.9	53.0
MIX2	49.99	83.2	41.9	98.1	82.4	15.5	91.3	7.0	42.6
MIX3	47.99	81.0	38.1	94.9	77.4	13.8	88.3	8.0	56.9
MIX4	47.73	80.7	35.15	96.7	77.7	12.7	90.8	5.0	50.6

Table 6. Results of reduction on MIX2 with different reductants.

Reductant	Oversize (metallic)		Undersize (to magnetic separation)				
			Concentrate			Tailing	
	FeT (%)	wt (%)	FeT (%)	wt (%)	MD (%)	FeT (%)	wt (%)
Coarse graphite	90.1	43.6	85.3	8.8	96.7	7.5	47.6
Fine graphite	89.2	41.9	82.6	10.6	91.2	7.0	47.5
Coarse coke	89.7	39.4	81.3	12.8	93.3	3.3	46.1
Fine coke	88.5	29.5	76.6	13.4	93.4	7.1	50.5

Table 7. Results of reduction on MIX2 with different lime additions.

Lime (%)	Oversize (metallic)		Undersize (to magnetic separation)				
			Concentrate			Tailing	
	FeT (%)	wt (%)	FeT (%)	wt (%)	MD (%)	FeT (%)	wt (%)
0	77.9	42.1	67.6	12.7	97.9	5.9	36.0
2	78.9	49.0	67.7	13.2	98.4	4.0	37.8
5	76.5	51.3	60.3	14.5	99.0	5.0	34.2
10	76.0	62.4	67.4	16.3	95.5	5.5	21.3

4. Conclusions

This study demonstrates the technical feasibility of recovering metallic iron nuggets from three steelmaking by-products—sludge, mill scale, and EAF dust—via reduction trials. The key variables influencing nugget formation and iron recovery are the type of reductant and the addition of lime as a flux. The best performance was achieved using composite pellets with equal shares of the three by-products, coarse graphite reductant, and 10wt% lime, under which 62.4wt% of the sample converted to metallic iron nuggets with metallization above 99%. These findings highlight a practical pathway to fully upcycle the three major steelmaking by-products into DRI-grade metallic feedstock, offering a closed-loop recycling route for DRI–EAF mills with zero solid waste generation from these streams.

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