

Recycling Evaluation of Mill Scale in Electric Arc Furnace

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ARTICLE INFO

Article history:

Received 04 Dec. 2013

Accepted 28 Apr. 2014

Available online 31 Aug. 2014

Keywords:

Mill scale

Electric arc furnace

Reduction

Oxygen consumption

ABSTRACT

A considerable amount of mill scale is generated from steel making plants annually. Although some industries use it as raw material, since it contains iron in the form of FeO, Fe₂O₃, and Fe₃O₄, it can be considered as a valuable metallurgical raw material in iron and steel making industry as well. Thus, the aim of this study was to evaluate the possibility, efficiency, and consequences of the reduction of mill scale in the electric arc furnace. Accordingly, different portions of mill scale were charged into an electric arc furnace (with two different charging methods) and the results were compared with reference heats. Results revealed that charging mill scale into electric arc furnace decreases oxygen and carbon powder consumptions, while negatively influences on production time, energy and coke consumptions, and slag composition. Moreover, reducibility evaluations based on tapping weight and oxygen consumption showed that almost %14.9 of mill scale is reduced in electric arc furnace.

1. Introduction

High amount of by-products, in the form of oily mill scale sludge is generated every year in each section of steel making plants. The strict environmental regulations as well as the valuable metallic content cause the ability to recycle mill scales become an important issue. Even though mill scale is being used in industries such as cement, powder metallurgy, ferroalloy, agriculture, etc., since it contains % (65-70) iron in the form of FeO, Fe₂O₃, and Fe₃O₄, it can be considered as a valuable metallurgical raw material for iron and steel making industry [1, 2]. Accordingly, to recycle the iron content, briquettes consisting of mill scale, carbon and other wastes are charged into

blast furnace due to its reducing atmosphere. In addition, the scales produced in stainless steel making plants contain considerable alloying elements such as chromium and nickel. In this case, the recovery of these elements is so crucial that they were charged into the electric arc furnace (EAF) during the melting of stainless steel scrap [3]. Another method has been developed for the injection of mill scale into EAF slag in order to use the FeO capacity of mill scale to achieve appropriate foamy slag. Danilov[4] reported that applying this method results in well-foamed slag and consumption of electric power is cut by 10-30 kWh/ton. However, this method requires installation of additional mill scale injection equipments that

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may restrict the application.

About 750 tons of mill scale sludge is generated annually in Iran alloy steel company (IASCO) that are currently sold to relative industries. However, there has been a big tendency to recover the valuable iron content in the production process. In this regard, the present study was conducted to evaluate the possibility, efficiency, and consequences of the reduction of mill scale in the electric arc furnace. The metal recoveries from the scales were then estimated based on the information and results of the C-O reactions and metal recovery obtained from the present trial heats. Finally, the economical aspects of these changes were assessed.

2. Experimental

The scales generated from steelmaking, heavy and light section mill plants were collected and dried. Table 1 shows the iron oxides content of the scales obtained from X-ray diffractions (XRD) analysis performed by a Philips X'pert high score X-ray diffractometer. In order to evaluate the reduction behavior of mill scale in EAF, three types of heats were produced: i) reference heats designated as type A, ii) charging mill scale in addition to conventional charging (type B), and iii) replacing mill scale with a part of the conventional charge (type C). Except for type C heats, 8 and 42 tons of scrap and direct reduced iron (DRI) were charged into the furnace, respectively. For those heats which contained mill scale (type B and C), the big bags of the mixture of mill scale together with coke and lime (as reducing agents) were charged into the furnace through scrap charging bucket. The summary of the big bag coke and lime additions proportional to the mill scale weight in each type of trial heats is listed in table 2. In case of type C, the scrap weight remained constant but the DRI weight reduced as much as mill scale weight. In each heat, when scrap was charged into the EAF, the electrodes started arcing and when almost %80 of the charge was melted, the injection of oxygen and carbon powder started to provide additional chemical energy as well as foamy slag. As melting was completed, DRI started to charge continuously. Moreover, different amounts of lime, dolomite and coke were added to the furnace during smelting.

In order to evaluate the FeO content of the slags, two slag samples were taken from the first and last foamy slag produced during smelting. Thereafter, the slag was grounded and 1 g of slag was then mixed with a mixture of 9.95 g lithium tetraborate and 0.05 g lithium iodide. The mixture was melted and cast into a disk and then analyzed for X-ray fluorescence (XRF). Finally, the results were compared with 10 reference heats to investigate the charging behavior of mill scale in EAF.

3. Results and Discussion

3.1. Theoretical calculations

In EAF, in the presence of coke and carbon injection into the melt, the reduction of mill scale will occur according to the following reactions [5]:



Considering the above equations as well as the iron oxides content of heavy section mill scale as our reference, we could calculate the obtained and consumed materials by the complete reduction of mill scale during EAF operation (table 3). To estimate the total energy consumption of the reduction process, enthalpy change (ΔH) of each reaction was calculated separately within the temperature of 298-1953 Kelvin as shown in equation (4) and converted to kWh, considering that each kWh equals 3600 kilo joules.

$$\Delta H = \Delta H_{298} + \int_{298}^{1953} \Delta c_p \quad [4]$$

Where ΔH_{298} is bond enthalpy and Δc_p is the specific heat capacity change of the reactions.

3.2. Discussion

Fig. 1 shows the power on time of the EAF operation versus mill scale weight charged to the furnace. In this figure, the heat types have been specified by different symbols. As can be seen, by charging mill scale to the furnace, in comparison with reference heats, arcing time increases about 6 and 3 minutes per mill scale ton in type B and C heats, respectively. The energy consumption of each heat is illustrated based on mill scale weight in fig. 2. The

Table 1. The iron oxides content of mill scales (obtained by XRD analysis) collected from different origins

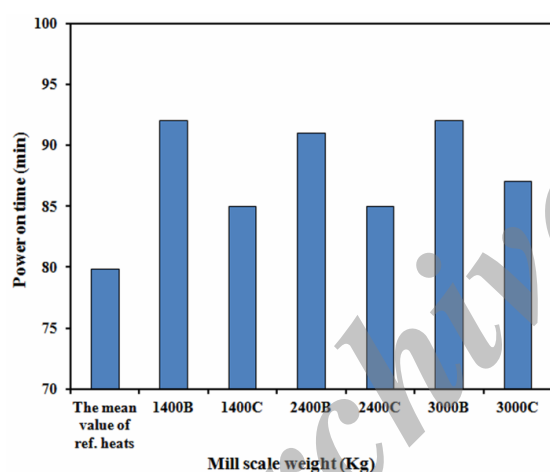
Mill scale origin	%Fe _t	%Fe ₂ O ₃	%Fe ₃ O ₄	%FeO
Steelmaking plant	75.92	15.7	25.2	59.1
Light section rolling mill	73.61	39	20.6	40.4
Heavy section rolling mill	74.82	24.4	18.9	56.7

Table 2. The summary of the big bag mill scale, coke, and lime weights in each B and C type of trial heats

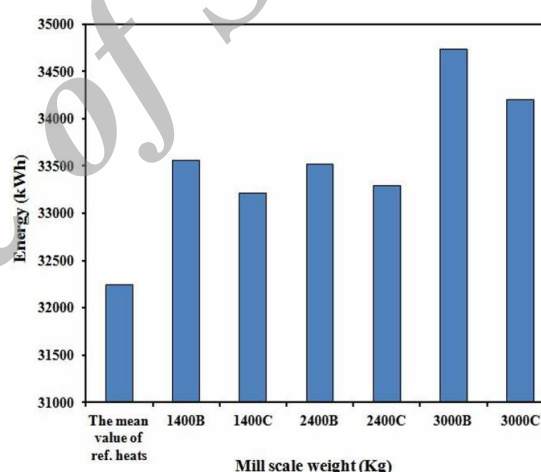
Mill scale weight (Kg)	Coke (Kg)	Lime (Kg)
1400	250	450
2400	400	600
3000	500	750

Table 3. The calculated obtaining and consuming materials by the complete reduction of one ton of mill scale

Reaction No.	Iron oxide content (Kg)	Achievable iron (Kg)	Required Carbon(Kg)	Achievable oxygen(Kg)	Required electric energy (kWh)
1	424.45	330.12	70.74	94.4	296
2	182	127.4	40.95	54.6	160.9
3	141.48	102.45	29.27	39.02	103
Sum	747.93	559.97	140.96	188.02	559.9

**Fig. 1.** Relationship between mill scale weight and power on time

consumed electric energy also increased about 769 and 594 kWh per mill scale ton for type B and C heats, respectively. These increments can be attributed to the melting of mill scale in the furnace and the endothermic behavior of iron oxides reduction process by carbon. Accordingly, in the presence of mill scale in EAF, more heat input is required and as a result, more electric power should be applied. It should be noted that because the lower DRI weight was charged to the furnace, with equal mill scale weight (3000 Kg), type C heat shows

**Fig. 2.** Relationship between mill scale weight and consumed electric energy

the lower power on time and energy consumption compared to type B.

Fig. 3 shows that by increasing mill scale weight in EAF, the oxygen consumption drops. In these trial heats, the average oxygen injected to the furnace was about 1097 m³ per heat for reference heats, whereas based on the values obtained from type B and C heats, it can be concluded that oxygen consumption reduces about 112 m³ per mill scale ton. In fact, because of the lower liquid mill scale density compared to liquid steel, they move to slag as

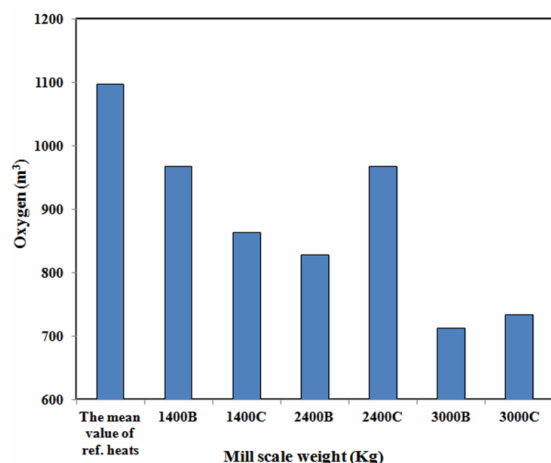


Fig. 3. Relationship between mill scale weight and consumed oxygen

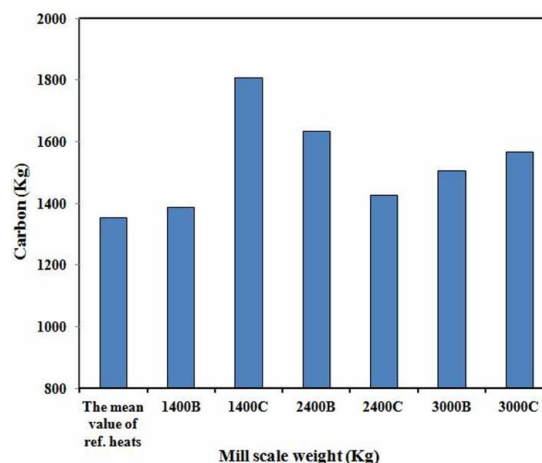


Fig. 4. Relationship between mill scale weight and consumed total carbon (coke and carbon powder) weight

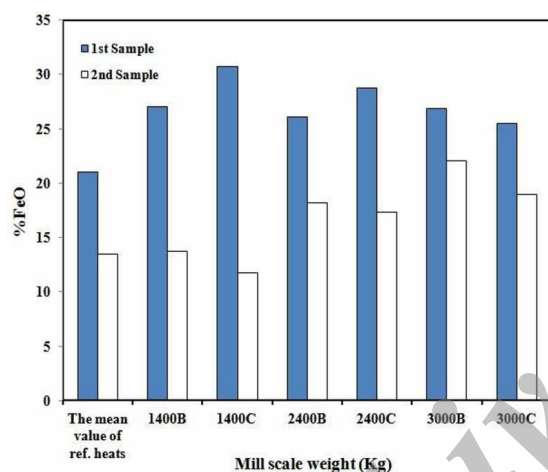


Fig. 5. Relationship between mill scale weight and the FeO content of the first and second slag sample

the charge was smelted. Slag viscosity decreases as its FeO content increased [6]. So, in the presence of considerable amount of mill scale (FeO) in slag, very low viscosity foamy slag is outpoured from the slag gate. At this moment, EAF operators stop the injection of further oxygen to the melt that leads to the reduction of oxygen consumption. It is worth mentioning that optimum foamy slag contains almost %20 FeO [7]. The more FeO in slag leads to higher refractory erosion, yield decrement due to Fe losses, and increasing energy consumption [6]. This phenomenon reveals that a portion of mill scale is not reduced in EAF and it is outpoured by the foamy slag. In fact, because slag is continuously produced in EAF and a huge

portion of it is outpoured in the form of foamy slag, a considerable amount of mill scale leaves the furnace without meeting reducing agents during EAF operation. Furthermore, the rest of them cannot be possibly reduced completely because their presence in the furnace as well as production time is limited and EAF atmosphere becomes oxidizing as the oxygen lance starts the injection. Consequently, based on the above explanations, it can be inferred that 112 m³ oxygen consumption reduction means that almost 150 Kg of each mill scale ton has been affected by reducing agents and only about %14.9 of mill scales have been reduced.

Fig. 4 depicts the total carbon (coke and injected powder carbon) consumption of each heat. Although some fluctuations can be observed in carbon consumption, it is clear that it has increased in type B and C heats. The average obtained carbon consumption of type A heats was about 1354 Kg per heat, while this value is about 1554 Kg for type B and C heats. This increment can be clearly attributed to the requirement of reducing agent in type B and C heats; therefore we had to charge extra coke to these heats.

The FeO content of two slag samples, taken from the first and last foamy slag of each heat are illustrated in fig. 5. Regardless of the amount of mill scale, primary foamy slags always showed higher FeO in comparison with the last one. This is rational since significant volume of oxygen is injected to the melt at the

Table 4. The charging materials, tapping weight, and the estimated reducibility of mill scale in the EAF

Heat type	Mill scale (Kg)	Scrap (Kg)	DRI (Kg)	Tapping weight (Kg)	Reducibility per mill scale tone (%)
C	3000	8000	39030	43200	11
C	2400	8000	39600	43700	26
A	-	8000	42030	44700	-

Table 5. A summary of final achievements by charging one ton mill scale into EAF through type B and C charging procedures

Heat type	Coke (Kg)	Carbon powder (Kg)	Oxygen (m ³)	Energy (kWh)	Production time (min)
B	-75	11.1	112	-769	-6
C	-75	11.1	112	-594	-3

beginning, while at the end carbon powder injection is dominant for reducing the oxides in slag (mainly FeO) as well as adjusting the carbon content of the melt. Nonetheless, the slag of the type B and C heats had higher FeO than the reference heats both at the beginning and the end of each heat because a portion of mill scale is transferred to the slag. It should be noted that the higher FeO content of type B and C heats is not desirable since it is likely to cause destructive influences as mentioned above.

In order to investigate the reducibility of mill scale in EAF on the basis of tapping weight, two type C heats and a reference heat (type A) were produced with the same charging materials weight (50 tons). It should be reminded that in type C heats, a portion of charging DRI was replaced with an equal weight of mill scale. The furnace was tried to be discharged completely with the least possible slag carryover. It was observed that the more DRI was replaced with mill scale, the more tapping weight decreased. This phenomenon also supports the above explanations concerning the partial reduction of mill scale in EAF and the transfer of a considerable amount of it into slag. Based on the obtained tapping weights and considering the reference heat weight as the maximum possible tapping weight for a 50 tons charging materials, and the fact that the maximum achievable iron from one ton mill scale is almost 560 Kg (table 3), the reducibility for each ton charging mill scale in EAF can be estimated. Accordingly, the calculated reducibilitys for two produced heat containing 3000 and 2400 Kg mill scale are %11

and %26, respectively. Although the accuracy of the estimated values has probably been affected by slag carryover and even production procedure (for example the amount of produced slag and injected materials in each heat, the number of foamy slag discharges, etc.), they are in agreement with the estimated value based on oxygen consumption. Thus, on the basis of both point of views, i.e. oxygen consumption and tapping weight, it can be confidently claimed that almost %14.9 of charged mill scale has been reduced in each trial heat. The charging material and tapping weight as well as the reducibility of mill scale in the EAF are tabulated in table 4.

The summary of total achievements concerning the charge of one ton mill scale into EAF (for both type B and C charging conditions) is shown in table 5. In this table, positive mark indicates that the item is profitable while negative mark indicates the opposite. Having mentioned items and their prices, besides preparation and storage costs, we can easily estimate the financial benefit of using one ton mill scale in EAF in any currency using the following equation:

$$\text{Benefit} = 83.4A - 75B + 11.1C + 112D - 769E - 6F - G \quad [5]$$

where A is the price of one Kg steel, B is the price of one Kg coke, C is the price of one Kg carbon powder, D is the price of one m³ oxygen, E is the price of each kWh electric energy, F is the price of one minute EAF production cost, and G is the preparation and storage cost for one ton mill scale. It should be noted that equation (5) is valid only for type B charging method.

Since there are many negative items in the equation, including the expensive EAF production time cost, and the reduction is not considerable to compensate them, we cannot expect benefit from recycling mill scale in EAF even with type B charging condition. However, equation (5) should be recalculated in each era based on new prices. Furthermore, it can be easily found that type C charging method is not beneficial because in this case efficient DRI is replaced with low reducible mill scale; so, the production yield is considerably reduced.

4. Conclusions

In the present study, with the purpose of the evaluation of recycling mill scale in EAF, several heats with different portions of mill scales and with different charging conditions (i.e. reference heat (type A), charging mill scales in addition to conventional charging (type B), and replacing mill scales with a part of conventional charge (type C)) were produced and the following conclusions were drawn:

1. In comparison with the reference heats, the power on time of type B and C heats increased about 6 and 3 minutes per mill scale ton, respectively.
2. The electric energy consumption increased about 769 and 594 kWh per mill scale ton for type B and C heats, respectively.
3. Because a considerable amount of mill scale is transferred to slag during production, oxygen consumption reduced about 112 m³ per mill scale ton in comparison with the reference heats. In addition, the average total carbon (coke and injected powder carbon) consumption increased about 200 Kg in each heat.
4. The FeO content of two slag samples, taken from the first and last foamy slag of each heat showed that the first sample always contains higher FeO in comparison with the second one. However, the FeO content of the foamy slag samples of type B and C heats was higher than that of the samples of reference heats.
5. Reducibility evaluations based on tapping weight revealed that only (11-26) % of mill scale is reduced in EAF, while more precise calculations on the basis of oxygen consumption showed that 14.9 % of mill scale has been reduced in each heat which is in

agreement with the above range.

6. In order to estimate the benefit of charging mill scale in EAF, equation (5) was obtained for type B charging condition based on the assessed items in the study. Moreover, it was found that type C charging method is not beneficial because in this case efficient DRI is replaced with low reducible mill scale so, the production yield is considerably reduced.

Acknowledgment

The authors would like to thank Mr. A. A. Mokhtari, M. R. Jafarizadeh and, M. R. Nikraves from Technology Affairs and Steelmaking departments of IASCO, and Dr. M. Kalantar from Materials and Mining Engineering department of Yazd University for their supports of this project.

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