RECYCLING OF IRON AND STEELMAKING PLANTS WASTES

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Keywords

Waste-recycled, sulphur removal, magnetic separation, steelwork wastes utilization, statistical experimental design.

Abstract

As a result of the processes applied in the steel production, approximately 400 kg of waste is generated for every one ton of steel products. According to environmental regulations, these wastes must be disposed or stored in waste dams, which imposes a serious financial burden on iron and steel enterprises. In recent years, wastes with a high iron content has been recovered and returned to the steelmaking processes, replacing ore and contributing to a more efficient use of resources. However, despite the high iron content, it is not possible to use high sulphur content wastes as raw material in steel production. In this study, it is aimed to increase the utilization possibilities of these wastes as secondary raw material by reducing the content of sulphur in the concentrate by magnetic separation. It was shown that 33.34% of the wastes can be recycled with 54.90% iron recovery and 74.43% sulphur removal after dry magnetic separation experiments while 14.66% of the wastes can be recycled with 28.60% iron recovery and 89.93% sulphur removal after wet magnetic separation experiments. These removals correspond to 0.03% and 0.01% sulphur contents in the concentrates after dry and wet magnetic separations, respectively, and the concentrates can be blended back into the main raw material.

DEMİR ÇELİK TESİS ATIKLARININ GERİ DÖNÜŞÜMÜ

Anahtar Kelimeler

Atık geri dönüşümü, kükürt giderme, manyetik ayırma, çelik atıkları kullanımı, istatistiksel deneysel tasarım.

Öz

Çelik üretiminde uygulanan işlemler sonucunda her bir ton çelik ürün için yaklaşık 400 kg atık oluşmaktadır. Çevre mevzuatına göre bu atıkların bertaraf edilmesi veya atık barajlarında depolanması gerekmektedir ki bu da demir-çelik işletmelerine ciddi bir mali yük getirmektedir. Son yıllarda demir içeriği yüksek atıkların geri kazanılması ile cevherin yerini alacak şekilde çelik üretim proseslerine geri döndürülmekte ve böylece kaynakların daha verimli kullanılmasına katkı sağlanmaktadır. Ancak yüksek demir içeriğine rağmen yüksek kükürt içeriğine sahip atıkların çelik üretiminde hammadde olarak kullanılması mümkün değildir. Bu çalışmada manyetik ayırma ile konsantredeki kükürt içeriğinin azaltılması ile bu atıkların ikincil hammadde olarak kullanım olanaklarının artırılması amaçlanmaktadır. Kuru manyetik ayırma deneyleri sonrasında atıkların %33,34'ünün %54,90 demir geri kazanımı ve %74,43 kükürt giderimi ile geri dönüştürülebileceği, yaş manyetik ayırma sonrası atıkların %14,66'sının %28,60 demir geri kazanımı ve %89,93 kükürt giderimi ile geri dönüştürülebileceği gösterilmiştir. Kuru ve yaş manyetik ayırmalardan sonra elde edilen konsantrelerin kükürt içerikleri sırasıyla %0,03 ve %0,01 olup, bu konsantreler tekrar ana hammaddeye harmanlanabilir niteliktedir.

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1. Introduction

The iron and steel industry create output and employment in hundreds of other industries all over the world. Considering all of the industries with direct, indirect and induced impacts, the steel industry offers more than $ 1,000 billion in economic output and nearly six million jobs. Steel is found utilization in a very large industrial sectors including automotive, construction, packaging and rail sectors without which modern society cannot remain sustainable. World crude steel production reached 1689.4 million tonnes (Mt) for the year 2017, up by 3.8% compared to 2016. The biggest steel producer country is China, and its crude steel production in 2017 is 831.7 Mt accounting for 49.2% of the world. Ranking 8th in the world total steel production with a share of 2.2%, Turkey's steel production in 2017 was 37.5 million tons of crude steel, with an increase of approximately 13% compared to the previous year. (Basson, 2018)

There are two main processes for crude steel production: blast furnace - basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) routes. Besides these two main routes, there are other routes such as open heart furnaces (OHF) used in steelmaking in Russia and Ukraine. 71.5% of the world's crude steel production is via BF-BOF route while 28% of that via EAF production route. The other methods are negligible and accounts for only 0.5% of total production (Basson, 2018). It was claimed that on average, solid wastes of 200 kg for the electric arc furnace (EAF) route and 400 kg for the blast furnace - basic oxygen furnace (BF-BOF) route were produced for the manufacture of one ton of steel (Worldsteel Association, 2018). The main solid wastes produced during crude steel production are slags (90% by mass), dust and sludge. These wastes are disposed or dumped to the waste dams which causes serious negative environmental impact as well as financial burden on the iron and steel industry. On the other hand, the World's economy currently loses a significant amount of potential secondary raw materials which are found in waste streams. It was reported that total solid waste generation in 2013 in the EU was about 2.5 billion tons of which less than 1 billion tons were reused or recycled therefore enormous amount of lost for the European economy was recorded. (European Commission 2015). Furthermore, EU published a directive on 30 May 2018 on the subject which states that "Waste management in the Union should be improved and transformed into sustainable material management, with a view to protecting, preserving and improving the quality of the environment, protecting human health, ensuring prudent, efficient and rational utilisation of natural resources, promoting the principles of the circular economy, enhancing the use of renewable energy, increasing energy efficiency, reducing the dependence of the Union on imported resources, providing new economic opportunities and contributing to long-term competitiveness. In order to make the economy truly circular, it is necessary to take additional measures on sustainable production and consumption, by focusing on the whole life cycle of products in a way that preserves resources and closes the loop" (European Commission 2018). According to the EU waste hierarchy, in waste management, the first priority is given to waste prevention, then to recycling, then to energy recovery and finally to disposal.

In this study, the utilization possibilities of BOF slags as a secondary raw material, taken from an iron and steel plant's waste landfills were investigated by decreasing sulphur content by dry and wet magnetic separation methods. Central Composite Design (CCD) which is one of the statistical experiment design methods was used to design magnetic separation experiments (Khuri and Mukhopadhyay, 2010). Iron recovery, sulphur removal rate and weight yield of the concentrate were accepted as dependent variables (response variables). After variance analysis, regression models were created for each dependent variable by using Stat-Ease Design Expert software version 11.

2. Scientific Literature Review

Over the past 20 years, the use of the steel industry's wastes has increased significantly. The recovery of high iron content wastes and their return to steel production processes instead of ore contributes to the more efficient use of resources. Other wastes have many uses in other industries; For example, while steelmaking slags are used as aggregates in road construction, blast furnace slags and dust are used in cement production instead of clinker (Worldsteel Association, 2018).

In Turkey, a number of steel production plants operating by basic oxygen furnace route are distributed mainly north-west part of Turkey. 420 kg of solid wastes are produced for each ton of steel production, and these solid wastes include mainly BOF slags, dust and sludge wastes. These wastes are disposed to nearby landfills that cause severe environmental problems, and only a small percentage is recycled (Alanyalı, Çöl, Yılmaz and

Karagöz, 2006; Lan, Liu, Meng, Niu and Zhao, 2017). In this respect, BOF slags with as much as 14-20% iron content (Ocal, 2014) are important and can be utilized as secondary source for steel production. However, the impurities such as sulphur and improper particle sizes limit their utilization as secondary raw materials. The use of these slags can be increased by removing the unwanted impurities to an acceptable level by means of concentration methods. These methods include crushing, sizing, magnetic separation, flotation and leaching (Li, 1999; Shen and Forssberg, 2003; Alanyalı, et al. 2006; Bilen, 2010; Menad, Kanari and Save, 2014; Ma and Houser, 2014; Lan, et al. 2017).

3. Materials and Methods

3.1. Materials

Basic oxygen furnace slags taken from an iron and steel production plant's waste landfills were used throughout the experimental work. The slags contained 18.33% Fe, %0.15 S, %0.56 P and %39.61 Ca. The samples were crushed to -1 mm with a jaw crusher and sieved into three size fractions: -1+0.3; -0.3+0.075; -0.075 mm. In this article, the results of the studies with -0.3 + 0.075 mm size fraction suitable for both wet and dry magnetic separation are given; experimental results of other size fractions where only wet or dry magnetic separation or other methods were studied are not given here. The studied fraction represents 46.57% of the total sample by weight. The chemical composition of the studied sample determined by XRF analysis (by Panalytical ZETIUM) and contained 18.62% Fe, %0.13 S, %0.66 P and %41.53 Ca.

Figures 1 (a) and (b) show the XRD (by Panalytical EMPYREAN)and SEM-EDS (by Hitachi Regulus 8230 FE-SEM) patterns of studied sample. In the XRD pattern, iron, calcium and sulphurous compounds are observed. Although phosphorus was not seen in the XRD pattern, low content of phosphorus was detected by XRF analysis. XRD and SEM-EDS patterns proved that Porlandite ($Ca(OH)_2$), Larnit ($2CaOSiO_2$), Brownmillerite ($Ca_2(Al,Fe)_2O_5$), Vustit (FeO), Calcite ($CaCO_3$), Magnetite (Fe_3O_4), Lime (CaO) were present in the sample. As it can be observed from Figure 1 that the peaks in the EDS pattern and the peaks in the XRD graphs overlap and indicate the same minerals. The SEM images also show that these minerals are locked with each other and difficult to be liberated even by fine grinding.

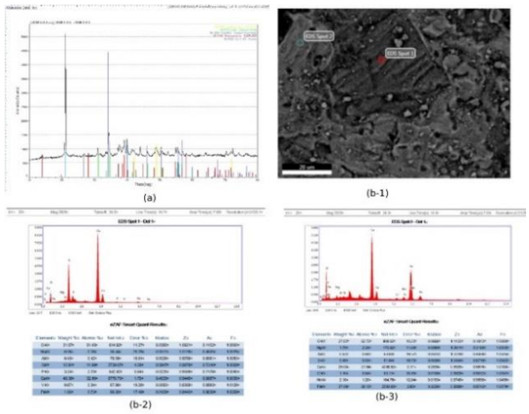

Figure 1. XRD (a) and SEM-EDS (b) Patterns of Studied Sample

3.2. Methods

Two different laboratory size magnetic separators, dry and wet type, were used to increase iron content and to decrease sulphur content of the studied material. Carpco Laboratory High-Intensity Induced-Roll Magnetic Separator which is a free fall type separator produced by Outokumpu Technology, Inc was used as dry magnetic separator. Its magnetic field strength is adjustable between 0 to 20 kilo gauss.

Master Magnet M5695 model laboratory type wet magnetic separator was utilized in the wet magnetic separation experiments. Pulp is fed manually to the magnetic separator which has three magnetic matrixes. The magnetic field strength can be set up to 25 kilo gauss from the control unit. The current intensity (ampere) can be adjusted in the device used, and the voltage intensity (volt) is read from the panel. The magnetic field strength was calculated by using the tension-generated magnetic field (gaussian) relationship given in the user manual of the device.

In the experimental studies, the effects of magnetic field strength, feed rate and drum rotational speed on dry magnetic separation (DMS) were examined while the effects of magnetic field strength, feed rate and solid ratio were examined on wet magnetic separation (WMS) as independent variables (parameters). After each magnetic separation experiments, two products were obtained: magnetics and non-magnetics. Magnetics fraction was called as concentrate while non magnetics as tailings. Iron and sulphur content of the concentrate and tailings were analysed by XRF, and iron recovery (R Fe; %), sulphur removal rate (S_{Rem}, %)and weight yield (WY, %) as dependent variables (response variables) were calculated from the equations 1 to 3 as given below:

$$R\ Fe\ (\%) = \frac{C*cfe}{F*ffe} * 100 \quad (1)$$

$$S\ Rem\ (\%) = \frac{F*f_S - C*c_S}{F*f_S} * 100 \quad (2)$$

$$WY\ (\%) = \frac{C}{F} * 100 \quad (3)$$

where, C and F are the amounts of concentrate and feed, respectively; c_{fe} and c_s are the iron and sulphur contents of concentrate, respectively; f_{fe} and f_s are the iron and sulphur contents of feed, respectively. Stat-Ease Design Expert software version 11 was used for statistical design and to obtain mathematical models of the response variables. Due to the design features of the magnetic separators used and in terms of practicality in setting the parameters, the alpha (α) coefficient used in the calculation of the axial points in dry and wet magnetic separations is taken as 1.4 and 2, respectively. In this study, independent variables (parameters) and their levels are given in Table 1 for dry and wet magnetic separation experiments. The levels for the factors were determined by preliminary experiments.

Table 1

Independent Variables and Levels for Magnetic Separation Experiments

Independent Variables (Parameters)						
DMS		Levels				
Fac.	Unit	-α	-1	0	1	+α
A	Gauss	20	100	300	500	580
B	g min^{-1}	82	90	110	130	138
C*	rpm	4	10	25	40	46
WMS				Levels		
A	10^3Gauss	2.5	10.6	14.3	14.7	14.8
B	g min^{-1}	10	15	20	25	30
C**	%	3	6	9	12	15

A: Magnetic field strength; B: Feed rate; C*: Drum rotational speed; C**:Solid ratio

4. Results and Discussion

The number of experiments with axials points in CCD was planned as 20 experiments for 3 parameters. All experiments were carried out randomly, and the results are given in Table 2.

As can be seen from Table 2, iron recovery, sulphur removal and weight yield were obtained as 54.90%, 74.43% and 33.47%, respectively at experiment 7 (100 Gauss, 130 g min^{-1}, 40 rpm) for DMS experiments. Iron recovery, sulphur removal and weight yield were obtained as 28.60%, 89.93% and 14.66%, respectively at experiment 9 (2500 Gauss, 200 g min^{-1}, 9%)) for WMS experiments. Although iron recovery seemed to be low at wet magnetic separation experiments, sulphur removal was obtained as nearly 90% which makes the BOF slags suitable for recycling.

Table 2. Design Matrix and Results of DMS and WMS Experiments

No	Coded values of factors			Dry Magnetic Separation			Wet Magnetic Separation		
	A	B	C	R_{Fe} (%)	S_{Rem} (%)	WY (%)	R_{Fe} (%)	S_{Rem} (%)	WY (%)
1	-1	-1	-1	65.43	57.27	50.60	75.67	41.33	58.30
2	1	-1	-1	89.97	16.83	25.92	94.63	6.84	88.89
3	-1	1	-1	60.14	60.11	45.60	75.60	41.69	23.29
4	1	1	-1	88.89	22.34	81.49	96.72	16.74	87.80
5	-1	-1	1	57.68	71.53	37.07	66.02	48.32	49.57
6	1	-1	1	84.63	27.86	25.68	97.36	11.60	91.14
7	-1	1	1	54.9	74.43	33.47	68.05	45.81	52.27
8	1	1	1	85.71	27.09	77.60	97.03	13.51	91.07
9	-α	0	0	43.16	72.33	27.06	28.60	89.93	14.66
10	+α	0	0	92.75	12.84	65.90	98.77	5.87	94.64
11	0	-α	0	86.87	24.11	78.96	90.52	13.34	83.21
12	0	+α	0	91.36	20.00	80.24	95.51	14.24	86.04
13	0	0	-α	54.37	59.29	42.40	95.16	26.58	85.71
14	0	0	+α	53.43	45.21	44.22	92.80	16.36	84.44
15	0	0	0	87.04	16.41	59.36	86.88	31.75	69.55
16	0	0	0	89.04	15.32	78.87	89.30	22.50	79.39
17	0	0	0	91.14	39.02	89.12	96.11	19.98	82.66
18	0	0	0	84.62	18.66	68.96	92.46	17.90	82.44
19	0	0	0	91.54	20.94	81.80	88.91	23.72	78.24
20	0	0	0	86.29	26.03	73.58	76.55	28.76	73.76

The experimental results were subjected to variance analysis for three response variables (iron recovery, sulphur removal rate and weight yield). As a result of variance analysis, the regression models were created for coded factors. Reduced ANOVA tables were prepared by eliminating statistically insignificant terms from the model with 95% confidence interval.

There are two main indicators that determine the effectiveness of a model: the coefficient of determination (R^2) and predicted R^2 (P-R^2). The consistency of a model with experimental data is represented by R^2 value which is the proportion of the variance in the dependent variable. Further, the power of a model is determined by P-R^2 which is a measure of how well the model predicts a response value (Khuri and Mukhopadhyay, 2010) Both indicators are also presented at the reduced ANOVA tables. The results were also examined by graphically. Reduced ANOVA result for dry and wet magnetic separation experiments are given in Table 3 for three response variables according to magnetic separation experimental results. Statistically insignificant terms were eliminated from the models with 95% confidence interval.

4.1. Dry Magnetic Separation (DMS) Experiments

According to ANOVA results of DMS, three regression models were created for iron recovery, sulphur removal rate and weight yield, and given in equations 4-6, respectively. Proposed models by software for all three response variables are significant as p values of models are less than 0.05. p values of Lack of fit for all models are greater than 0.05 which indicates experimental error is statistically insignificant.

$$RFe\ (\%) = 88.12 + 13.14\,A + 0.057\,B - 1.46\,C - 5.23\,A^2 - 8.74\,C^2 \quad (4)$$

$$SRem\ (\%) = 25.33 - 18.01\,A + 0.14\,B + 1.01\,C + 5.70\,A^2 + 8.11\,C^2 \quad (5)$$

$$WY\ (\%) = 72.52 + 7.60\,A + 6.34\,B - 1.63\,C + 14.51\,AB - 8.43\,A^2 - 9.22\,C^2 \quad (6)$$

The R^2 values are obtained as 0.9789, 0.8454 and 0.7571 for R_{Fe}, S_{Rem} and WY, respectively (Table 3). Graphical representation of predicted results versus actual results for all three response variables are given in Figs. 2 (a-c). As can be seen from the graphs, the R_{Fe}, S_{Rem}, and WY values estimated from the models represent the experimental results by approximately 98%, 85% and 76%, respectively which indicates the high consistency of the model for R_{Fe} and S_{Rem} while relatively the low consistency of the model for WY.

Table 3. The Results of Analysis of Variance (reduced ANOVA) for Three Response Variables for DMS and WMS

DMS		R_{Fe} (%)	S_{Rem} (%)	WY (%)
p Values	Model	<0.0001	<0.0001	0.0020
	A	<0.0001	<0.0001	0.0354
	B	0.9369	0.9551	0.0720
	C	0.0571	0.6873	0.622
	AB	-	-	0.0074
	A^2	<0.0001	0.0102	0.0053
	B^2	-	-	-
	C^2	<0.0001	0.0008	0.0029
	Lack of fit	0.5019	0.3790	0.2515
	Std. D.	2.82	9.86	12.95
	R^2	0.9789	0.8454	0.7571
	P R^2	0.9376	0.4224	0.2337
WMS		R_{Fe} (%)	S_{Rem} (%)	WY (%)
p Values	Model	<0.0001	<0.0001	<0.0001
	A	<0.0001	<0.0001	<0.0001
	B	0.5391	0.5903	0.4309
	C	0.4000	0.7133	0.5092
	A^2	<0.0001	<0.0001	0.0008
	B^2	-	0.0369	-
	C^2	-	-	-
	Lack of fit	0.8270	0.5481	0.0813
	Std. D.	5.45	5.20	8.59
	R^2	0.9162	0.9476	0.8835
	P R^2	0.8043	0.8561	0.7663

As can be seen from Table 3, the P-R^2 values are obtained as 0.9376, 0.4224 and 0.2337 for R_{Fe}, S_{Rem} and WY, respectively. These figures indicate high power for R_{Fe} while relatively low power for S_{Rem} and WY in comparison with R_{Fe}.

In a statistical design, factors that cause variability in the performance of a system but cannot be controlled called as noise factors (Steinberg and Bursztyn, 1998). It is noteworthy to point out that the weakest model obtained in the experiments is the model created for weight yield in dry separation. The correlation coefficient of this model was 75.71%. The main reason for this is thought to be the high amount of magnetic clustering. This is a noise factor in the system and causes uncontrolled fluctuation in the amount of material coming to the magnetic product. The high correlation coefficients of the models obtained in iron recovery and sulphur removal in dry separation indicate that the selectivity could be maintained somewhat despite magnetic clustering.

The main effects of parameters on R_{Fe} (%), S_{Rem} (%) and

WY (%) are given in Figs. 2 (d-f), respectively. As it can be seen from the ANOVA Table (Table 3) and Figs. 2 (d-f), the most effective parameter for all response variables is the magnetic field strength (A). Both linear and quadratic effects of magnetic field strength are found to be significant for all response variables. Linear effects of feed rate (B) and drum rotation speed (C) are found to be insignificant for all models while quadradic effect of drum rotational speed is found effective for all models.

When the variance analysis results of the weight yield are examined (Table 3), it is seen that the interaction between the magnetic field strength (A) and the feed rate (B) is statistically significant. This interaction is also shown in Fig. 3 as a three-dimensional graphic.

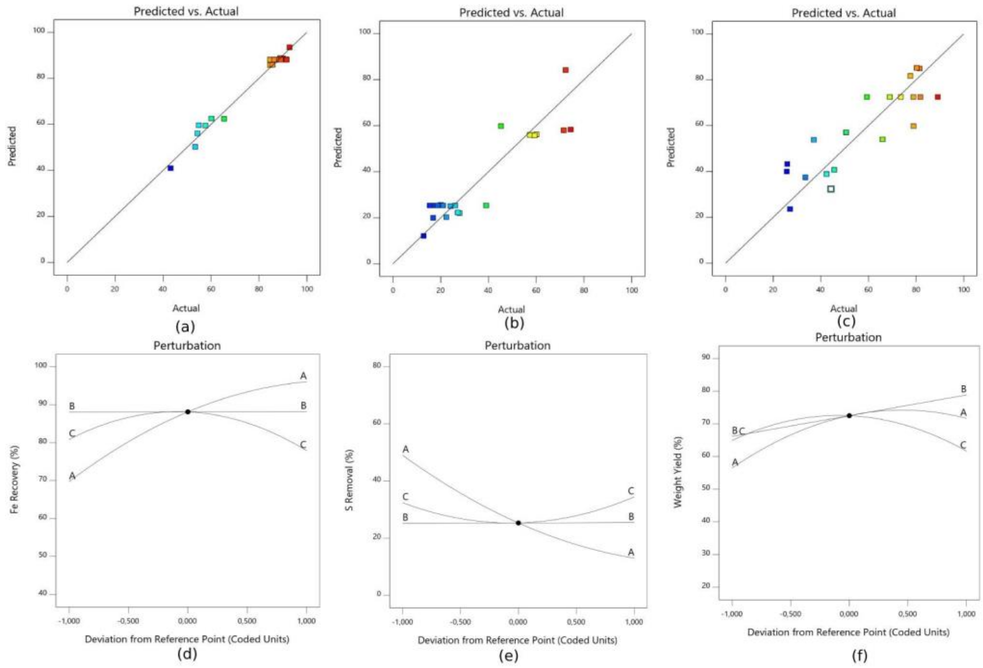

Figure 2. Graphical Representations of Analyzes for DMS: Predicted Versus Actual (a:R_{Fe}; b:S_{Rem}; c:WY) and Main Effects of Parameters (d:R_{Fe}; e:S_{Rem}; f:WY)

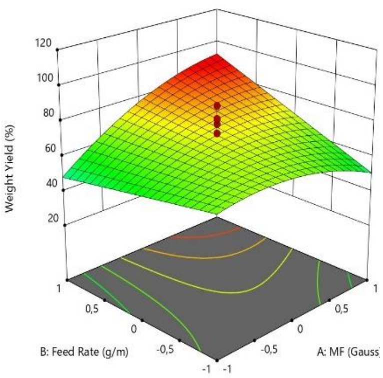

Figure 3. AB Interaction on WY for DMS.

As can be seen in Fig. 3, increasing the magnetic field strength caused a decrease in WY at low feed rate and an increase in high feed rate. This indicates that the effect of magnetic field intensity on the yield depends on the feed rate. This fact proves the interaction between these two parameters.

4.2. Wet Magnetic Separation (WMS) Experiments

Table 3 shows the reduced ANOVA result for three response variables according to wet magnetic separation experimental results. Three regression models were created for iron recovery, sulphur removal rate and weight yield, and given in equations 7-9, respectively. Statistically insignificant terms were eliminated from the model with 95% confidence interval. Proposed models by software for all three response variables are significant as p values are less than 0.05. p values of Lack of fit for all models are greater than 0.05 which indicates experimental error is statistically insignificant.

$$RFe\ (\%) = 90.47 + 15.05\ A + 0.86\ B - 1.18\ C - 6.67\ A^2 \quad (7)$$

$$SRem\ (\%) = 23.75 - 18.54\ A + 0.72\ B - 0.49\ C + 6.19\ A^2 - 2.34\ B^2 \quad (8)$$

$$WY\ (\%) = 78.33 + 20.96\ A - 1.74\ B + 1.45\ C - 6.84\ A^2 \quad (9)$$

R^2 values which represent the consistency of the models are obtained as 0.9162, 0.9476 and 0.8835 for R_{Fe}, S_{Rem}, and WY, respectively (Table 3). Graphical representation of predicted results versus actual results for all three response variables are given in Figs. 4 (a-c). As can be seen from the graphs, the R_{Fe}, S_{Rem}, and WY values estimated from the models represent the experimental results by approximately 92%, 95% and 88%, respectively which indicates the high consistency of all models. The fact that the correlation coefficients obtained for all response variables in wet magnetic separation are above 88% indicates that the uncontrollable noise factors are less effective in wet magnetic separation.

Table 3 also shows that P-R^2 values which represent the power of the models are obtained as 0.8043, 0.8863 and 0.7663 for R_{Fe}, S_{Rem} and WY, respectively. These values of P-R^2 indicate high power for all models

The main effects of parameters for R_{Fe} (%), S_{Rem} (%) and WY (%) are given in Figs. 4 (d-f), respectively. As it can be seen from the ANOVA Table (Table 3) and Figs. 4 (d-f), the most effective parameter for all response variables is the magnetic field strength (A). Both linear and quadratic effects of magnetic field strength are found to be significant for Iron recovery, sulphur removal rate and weight yield of the concentrate. Linear effects of feed rate (B) and solid ratio (C) are found to be insignificant for all models while quadradic effect of feed rate is found effective for sulphur removal.

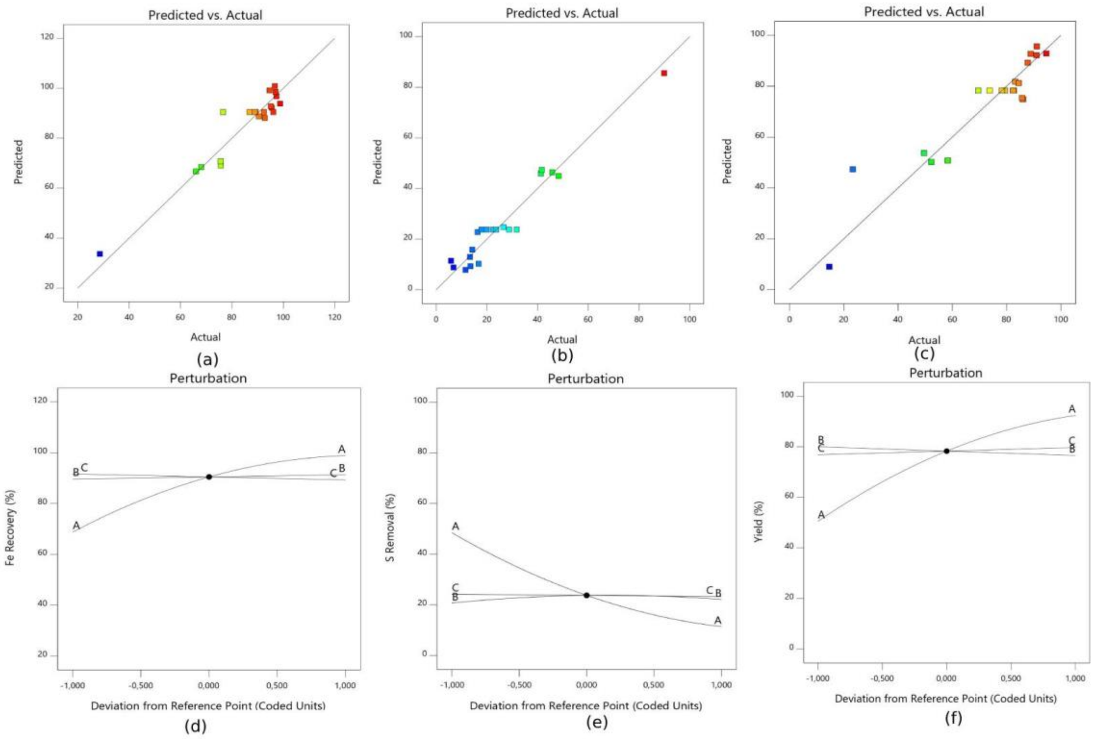

Figure 4. Graphical Representations of Analyzes for WMS: Predicted Versus Actual (a:R_{Fe}; b:S_{Rem}; c:WY) and Main Effects of Parameters (d:R_{Fe}; e:S_{Rem}; f:WY)

When the recovery of BOFs by magnetic separation are searched in the literature, studies performed by Alanyalı 2006, Menad 2014 and Lan 2017 have drawn attention.

In the first study, performed by Alanyalı 2006 by dry magnetic separator, was shown that the drum was the most effective parameter on the recovery of magnetic product. However, many data such as sulfur content, which have a significant effect on the recycling of iron, were not discussed in this study.

Menad 2014 has revealed the relationship between grinding type and grain size with both dry and wet magnetic separation efficiency in this study.

In the study presented by Lan 2017, the recovery of iron according to size fractions was studied by magnetic separation (wet or dry not mentioned) without no data on sulfur removal.

5. Conclusions

Recycling of iron and steel production plant wastes has been studied and the results of dry magnetic separation experiments showed that approximately one third of the wastes (33.47%) can be recycled with 54.90% iron recovery and 74.43% sulphur removal. This removal corresponds to 0.03% sulphur content, and the concentrate can be blended back into the main raw material. The results of wet magnetic separation experiments showed that 14.66% of the wastes can be recycled with 28.60% iron recovery and 89.93% sulphur removal. This removal corresponds to 0.01% sulphur content, and the concentrate can be blended back into the main raw material.

The results obtained from two experimental sets, including dry and wet magnetic separation with the size of -0.3 + 0.075 mm, showed that the magnetic field strength should be increased to increase the iron recovery, but this negatively affected the sulphur removal rate. When trying to increase the sulphur removal rate, the iron recovery remains very low.

These removals correspond to 0.03% and 0.01% sulphur contents in the concentrates after dry and wet magnetic separations, respectively, and the concentrates can be blended back into the main raw material.

Finally, it has been shown that with a simple crushing-magnetic separation plant, the amount of wastes stored in the tailings dam and causing storage and environmental problems can be reduced.

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Contribution of Researchers

In this study; All three authors contributed equally to the planning of the studies, the realization of the experimental studies, and the interpretation of the results and the conversion of the results into reports.

Conflict of Interest

No conflict of interest has been declared by the authors.

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