Iranian Journal of Science & Technology, Transaction B, Engineering, Vol. 30, No. B3
Printed in The Islamic Republic of Iran, 2006

A STUDY OF LINER/LIFTER WEAR IN CHADORMALU SEMI-AUTOGENOUS MILLS*

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Abstract– Due to certain advantages in (semi-)Autogenous-Ball mill circuits in most of the high-throughput ore grinding units of mineral processing plants, much attention is paid to optimize mill performance. Despite the maturity of the grinding mill mechanical design, the efficiency of the grinding media has previously been ignored. Different liner materials and shapes are used in different situations (in a variety of ore types and operational conditions), but the best economically and operationally chosen for one operation is not the same for the other. In this research, the possibility of establishing a relationship between liner/lifter wear rate and variations in the composition (SiO_2% and FeO%) of an iron ore is investigated. The ore belongs to a magmatic high grade iron ore deposit located at Chadormalu mine in the province of Yazd, Iran. A significant change in the mineralogical composition of the ore was observed during the sampling days which resulted in the variation of the feed ore work index. Measurements and determination of liner/lifter wear rates and patterns concluded that the critical liner segments posed too much abrasion during ore grinding. By performing the metallurgical analysis of liner materials and after correlation of wear rate with ore composition, it was concluded that the homogeneity in the metallurgical microstructure of the alloyed steel (such as the uniform distribution and amounts of the constituent phases) has a great influence on the response of the liner/lifter to the variations of ore composition. Magnetite with a greater abrasion index than hematite, also in finer particles, is responsible for additional wear rate (abrasion) in liners, but hematite with greater toughness/grindability (work index) exists in the mill with larger particle sizes, thus it could produce wear on liner parts with less tolerance to impact as is the situation for martensitic steels.

Keywords– Liner wear, semi-autogenous mill, iron ore,liner alloy structure

1. INTRODUCTION

In recent years greater attention has been paid to fully and semi autogenous mills in the grinding sector of mineral processing technologies. Most commercial grinding media today is produced from martensitic low alloy steels. Both forged and cast grades are available, with the main advantages of these steels being their adaptability to most milling conditions and the favourable cost to wear ratios [5].

Chadormalu mine is one of the greatest iron ore deposits in Iran located 180 km northeast of Yazd province. Since 1997 it has been active in the production of iron concentrate. The plutonic iron ore mineralization in granite consists of mostly magnetite, hematite, martite, apatite, quartz and carbonates. The average composition of the ore is presented in Table 1. In general the ore is classified as high grade iron ores, rich in phosphorus with minor sulfur contents. In the processing circuit, the gyratory crushed ore reduced to 30 cm would finally be the feed to three similar 32'Φ semi-autogenous mills in parallel processing lines, each with a daily capacity of approximately 9400 tones of ore. The pulp in the mill

*Received by the editors November 20, 2004; final revised form November 23, 2005.
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would have the characteristics mentioned in Table 2. The quality of the mill product has its direct effect, either physically or chemically, on the following processes such as classification or flotation. In order to take advantage of the optimum performance in these circuits, a close control of the ore grinding conditions is necessary since any shortage in throughput, liner/lifter damage or changes in ore composition could bring unexpected casualties. Nowadays, increasingly detailed and complete predictions of mill behavior, including high resolution predictions of liner stresses and wear rates and detailed collisional energy spectra are made possible with DEM modeling [1]. In this work, an attempt was made to find a (possibly) reasonable relationship between variations in ore characteristics, together with liner quality and the amount of wear rate in different liner/lifter segments of semi-autigenous grinding mills. In Chadormalu, liner/lifter segments of SAG mills are supplied by three different domestic steel making companies: the Tabarestan Company, the Ravanshir Company and the Merat Poulad Company. The alloy structure of the liners/lifters are made up of pearlitic chromoly steel.

Table 1. The average composition of the Chadormalu iron ore [2]

Fe (%)	P (%)	S (%)	SiO_2 (%)
55.22	0.94	0.19	6.93

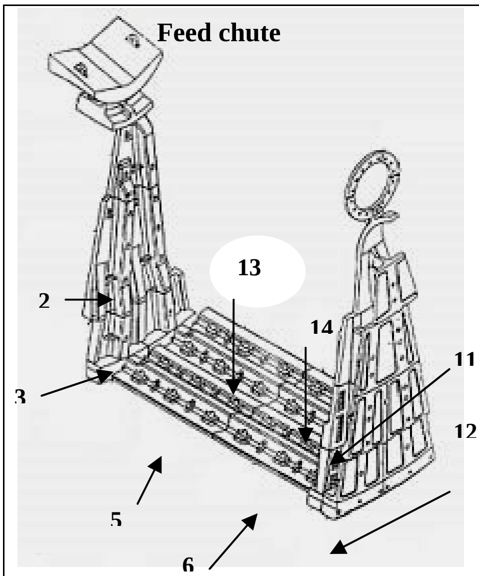
Table 2. The expected characteristics of the semi-autogenous pulps [3]

% Solids	Pulp density (g/cm^3)	Ore density (g/cm^3)	Out going pulp flow rate (m^3/h)	Average composition (%)
75	2.42	4.60	302	Fe: 56.23 FeO: 8.87

2. EXPERIMENTAL

The whole procedure is divided into three general sections. The first, gathering any required data concerning the iron ore mined and fed to the mill, the second, providing statistics on liner wear and consumption data according to each liner supplier company and the third, analysis of liner wear and metallurgical tests. A series of linear regressions were made for each pair of major chemical components (Fe_{total},SiO_2,FeO,Fe_3O_4) of the ore sampled during a determined time interval. Consequently the regression of SiO_2 with a total Fe content resulted in a strong correlation, and was used to estimate SiO_2 % in the ore for other periods. As for the iron ore itself, samples were collected (during ten successive days) from the feed and discharge of the SAG mill and the rest of the downstream circuits anywhere there was an access, after which the necessary chemical and physical analysis were performed to determine the characteristics of the ore under process. Weighing of new and worn (used) liner segments in certain downtime periods resulted in wear rate figures needed for regression analysis, as well as providing a comparable evaluation of each segment's wear pattern with respect to its location in the mill shell. A tri-dimensional view of the mill shell liners was made with AutoCAD to present more realistic conditions of wear in the mill.

Calculating the amounts of liner wear with respect to each segment's use of surface area on the inside mill shell, the so-called "critical" segments (considering the amounts and rates of wear as well as how a segment experienced wear) were recognized. For each wear rate data, FeO and SiO_2 contents in the ore were averaged for five sequential feed stockpiles which had been fed to the mill during each liner performance period. Among all parts of liners, there are 8 segments in direct contact with the mill load (balls and ore) which are presented in Fig. 1, together with their explanation.



Segment Code	Segment Name
2	Middle Feed Head Liner
3	Outer Feed Head Liner
5	Shell Liner Feed End-High
6	Shell Liner Discharge End-High
11	Middle Grate
12	Outer Grate
13	Shell Liner Feed End-Low
14	Shell Liner Discharge End- Low

Fig. 1. The location of different liner/lifter segments considered in the experiments [3]

3. RESULTS

a) Correlation among the variations of ore components

- The data used for the regression analysis is related to the SAG mill feed piles during the time period August 2001 to January 2002, which are named P55 up to P60. According to the regression parameters and the trends of the plots in Table 3 and Fig. 2, in general there exists a relatively strong correlation between the variations of total Fe and SiO_2 content of the feed ore which has a descending or reverse in trend. It is worth mentioning that those data which seemed out of range was omitted for better correlation. The corresponding amounts for SiO_2 are shifted 15 units forward each to distinguish the piles separately.

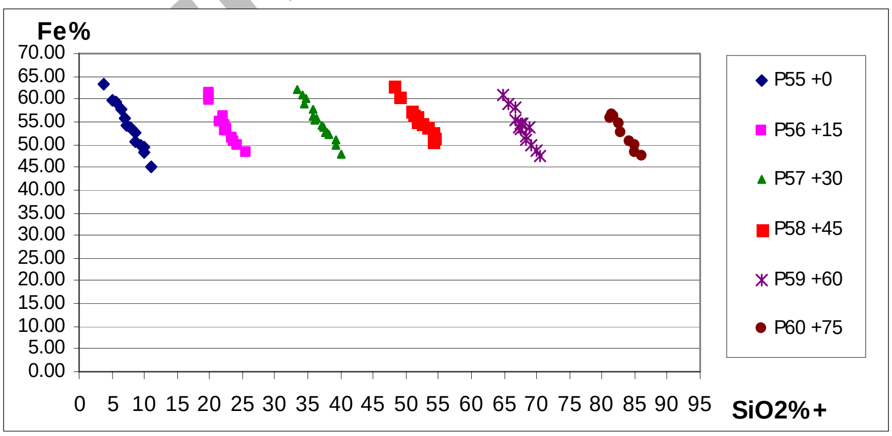


Fig. 2. The general trends of Fe-SiO_2 regression for the 6 feed piles

Similar investigations were done for other possible correlations for which the summary is mentioned here and tabulated in Table 4.

- FeO percent in the mill feed decreases with an increase in the SiO_2 percent, but is somewhat milder than Fe-SiO_2 variations.

- The inverse correlation between magnetite (mag.) and silica contents with a sharp slope represents the degree of sensitivity in the relative variations of these two components of the feed ore.

Table 3. Regression parameters for Fe-SiO_2 correlation

Pile No.	Regression equation Y:Fe , X: SiO_2	Correlation coefficient
P55	$y = -2.4218x + 72.528$	$R^2 = 0.9812$
P56	$y = -2.4189x + 72.048$	$R^2 = 0.9619$
P57	$y = -2.0041x + 68.6$	$R^2 = 0.9749$
P58	$y = -1.6016x + 66.437$	$R^2 = 0.9662$
P59	$y = -2.7135x + 75.374$	$R^2 = 0.8511$
P60	$y = -0.6889x + 58.81$	$R^2 = 0.3514$
Average slope of lines P55-P60		*Arctan(1.98)= 63.20*

Table 4. Summary of regression parameters for each correlation

Pile No.	Correlation coefficient value					
	x:SiO2 y:Fe	x:SiO2 y:FeO	x:SiO2 y:Mag	x:FeO y:Fe	x:Mag y:Fe	x:Mag y:FeO
55	0.98	0.69	0.78	0.68	0.76	0.97
56	0.96	0.70	0.74	0.84	0.87	0.99
57	0.97	0.20	0.22	0.20	0.20	0.98
58	0.98	0.03	0.21	0.20	0.38	0.94
59	0.92	0.43	0.48	0.76	0.77	0.98
60	0.97	0.31	0.26	0.13	0.55	0.95
$R^2_{Av.}$	0.96	0.39	0.45	0.47	0.59	0.97
Average Slope	-2.1	-1	-2.4	1.3	0.6	0.3
Slope (degrees)	64.54	45	67.38	52.43	30.96	16.70

The variation of correlation data among different feed piles could be directed to heterogeneities in the ore composition or analytical errors. Taking advantage of the good correlation between Fe_{total} and SiO_2 (Fig. 3), the regression equation was used to estimate the amounts of undetermined silica content in other feed piles, especially those used in wear analyses.

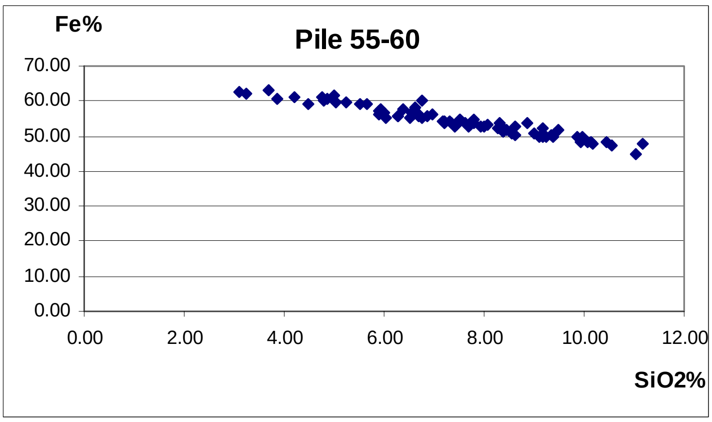


Fig. 3. Regression for Fe-SiO_2 (all piles together) Fe=-2.115 SiO_2 + 69.99

b) Results of ore analysis

All physical and chemical analyses were performed on samples represented over ten successive days. According to the work index measurements (Fig. 4), the values for the last three samples (corresponding days 8, 9 and 10) were significantly lower than the others. The total average work index determined about 14 KWh/t in the tests.

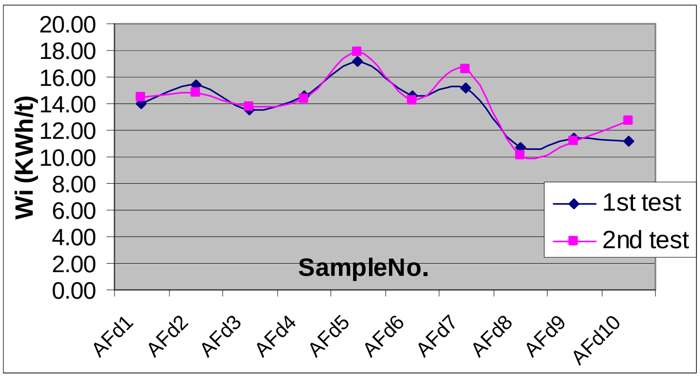


Fig. 4. Work index values of ten samples from the SAG mill feed

In the results of the chemical analysis of the pulp, it was found that the most variable values belong to the samples of ore fed to the SAG mill; Fig. 5 is an example for SiO_2 variations during the ten days in several pulp streams, which is useful only for comparison. The measured amounts of the ore constituents (for the feed to SAG mill) are available in Table 5, in which the data is presented in two separate feed piles which were fed during the ten days of sampling.

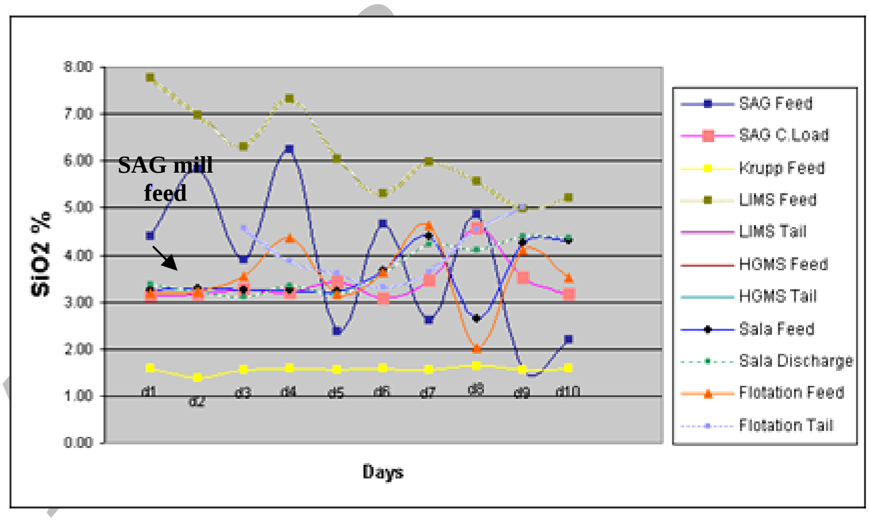


Fig. 5. Variation of SiO_2% of the ore (mill feed in comparison with other streams)

Table 5. The average composition of the feed ore determined in ten-days sampling

Composition →	SiO_2	Fe_T	FeO	Fe_2O_3	Fe_3O_4	Fe/FeO
Pile 88						
Average%	4.55	60.76	9.57	54.74	31.06	6.57
Variation Coef.	34.2	3.9	19.6	16.3	19.1	26.2
Pile 89						
Average%	3.18	60.31	12.7	43.85	40.96	5.02
Variation Coef.	47.2	3.4	21.9	27.3	21.9	31.4

One of the significant findings in these analyses was the difference in hematite/magnetite ratio of the two feed piles and its strong relationship with the work index or grindability of the ore. As is obvious from the data in Table 6 and the corresponding Fig. 6, there had been a comparable decrease in the strength of the ore for the second pile.

Table 6. Measurements of the work index and hematite/magnetite values for the feed ore

Sampling days	d 1	d 2	d 3	d 4	d 5	d 6	d 7	d 8	d 9	d 10
$\frac{Fe2O3}{Fe3O4}$	1.38	2.00	1.50	1.35	3.15	0.65	2.39	0.76	1.09	1.07
Average W_i (KWh/t)	14.23	15.09	13.66	14.48	17.53	14.44	15.84	10.38	11.29	11.91

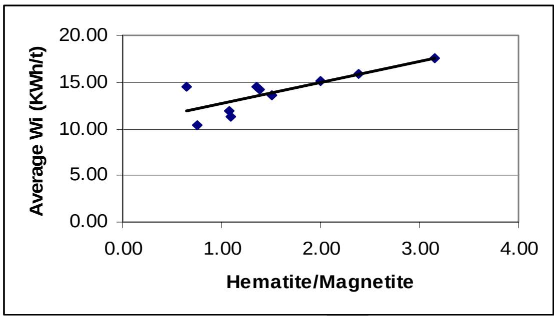


Fig. 6. Work index of the ore in relation to the hematite/magnetite variation

c) Metallurgical analyses and wear measurements

In order to explore the possible relationships between the wear pattern and alloy structure and composition of different liner/lifter segments, a series of metallurgical laboratory tests (metallography, quantometry, hardness and wear resistance) were done. The quantometry tests indicated the accordance of alloy structures with Woodsteel-140 Cr-Mo-Ni alloyed steels [4], which were the same for the three liner suppliers (Tabarestan, Ravanshir and Merat Poulad companies, hereafter represented by T, R and M respectively). In the sample codes (e.g. R2) the letter stands for the initials of the company name and the number is according to the segment codes presented in Fig. 1. Hardness measurements also determined the average values of 351 BHN for T and 375 BHN for both R and M companies [4]. The results of wear rate laboratory analysis (pin on disk method), used to estimate relative wear resistance of each of the companies' products, is shown in Fig. 7. The metallography tests in general showed a dominant pearlitic structure for all liner segments, but also some specificity for each of the supplier's products, due to the existence and amounts of other alloy phases such as ferrite, cementite, bainite and martensite (Fig. 8).

The results of the statistical analysis of liner wear measurements for segments made by the three providers are presented in Table 7. Segment codes are in correspondence with Fig. 1. With this data in hand, by calculating the proportion (percentage) of the mill shell devoted to each segment, and also considering the wear pattern and behavior of each liner/lifter segment, some liners were recognized as "critical", therefore in greater need of care and reinforcement. The general representation of this rating is presented in Fig. 9. Finally, some parts were determined as most exposed to abrasion, such as segment 2 with an arciform wear pattern or segment 11 (at the discharge grate) which experience the enlargement of grate holes.

Factors influencing linear/lifter wear are numerous and some crucial ones such as feed rate, pulp density and grinding media, as well as the pattern of load circulation inside the mill were not the subject of this study, however attention was focused on the ore composition and the possible liner wear predictions due to the mineralogical variation of the fed ore. Of course the electrochemical phenomena in a wet grinding media are also another issue. In completion of the investigation, attempts were made to find any correlation between ore composition and wear rate figures.

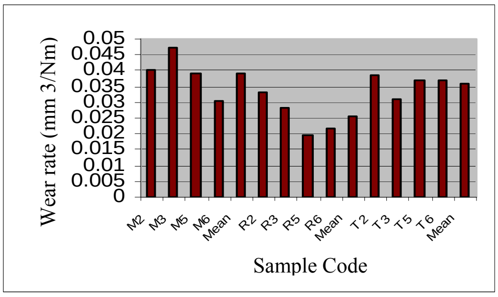


Fig. 7. Wear rate measurements for various liner/lifter segments

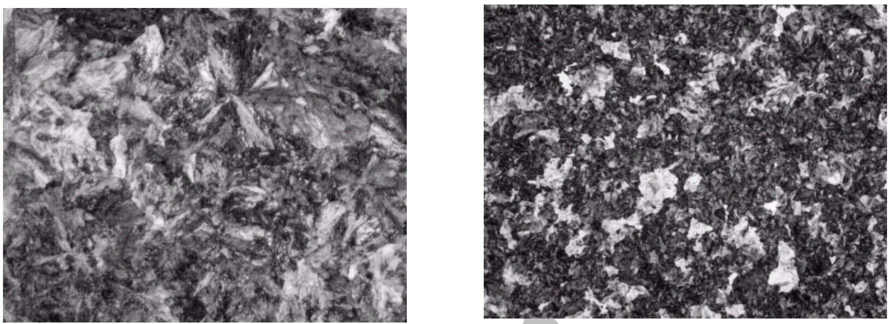


Fig. 8. Samples from the alloy structure of liners used in SAG mills [4]

Table 7. Wear measurements for different liner/lifter segments

SupplierCompany ► / Segment Code ▼	M		R		T	
	%	g/t_{feed}	%	g/t_{feed}	%	g/t_{feed}
2	39.80	24.33	40.00	23.13	37.79	23.26
3	24.38	6.69	25.87	5.22	28.75	7.40
5	39.90	22.50	36.10	19.83	43.83	23.38
6	33.34	18.56	34.35	18.59	35.20	17.92
11	39.51	12.36	32.34	9.88	44.36	13.46
12	20.93	5.37	12.97	4.51	27.26	5.83
13	40.30	17.60	30.84	11.62	44.84	18.43
14	29.49	12.77	28.98	12.16	30.84	12.53

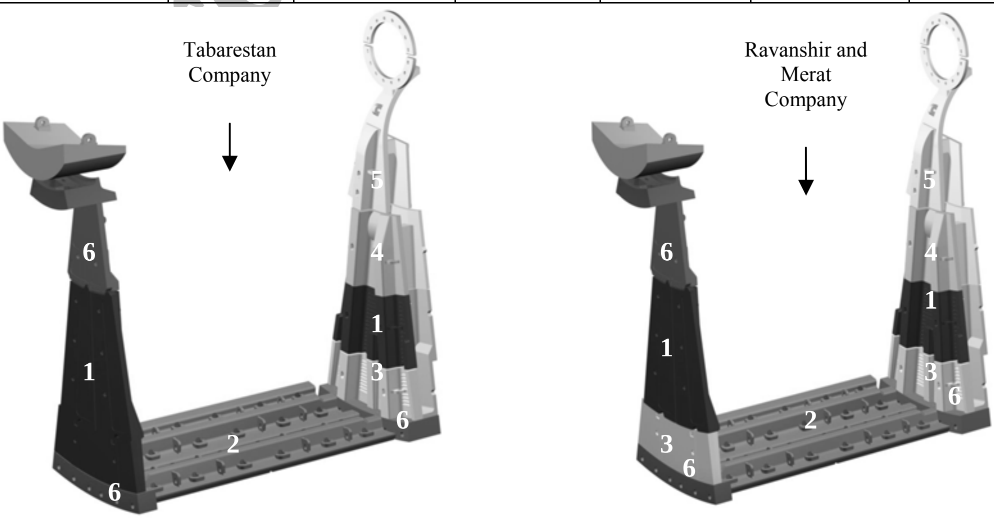


Fig. 9. Ranking of liner/lifter segments according to their wear rates and profiles, wear rates from high to low: 1 (critical), 2, 3, 4, 5, 6

Regression parameters of this correlation are presented in Table 8, which corresponds to the graphs in Figs. 10 to 12 for each liner producer. According to the correlation data and graphs, and also considering the results of the metallurgical tests, the following observations were obtained.

Tabarestan Company: In general, no strong correlation between SiO_2 or FeO variations in the ore with the rate of liner wear in Tabarestan Company products exist. The average percentage of manganese in this company's liner/ lifter segments (0.88%) was at least 0.1% greater than the average for the two other companies. The average percent of Cr and Mo (2.08, 0.32 respectively) were a little bit less than the average for Ravanshir and Merat Poulad. The average hardness value for Tabarestan products in Brinnell scale (351 BHN) was less than the average for Ravanshir and Merat (375 BHN each).

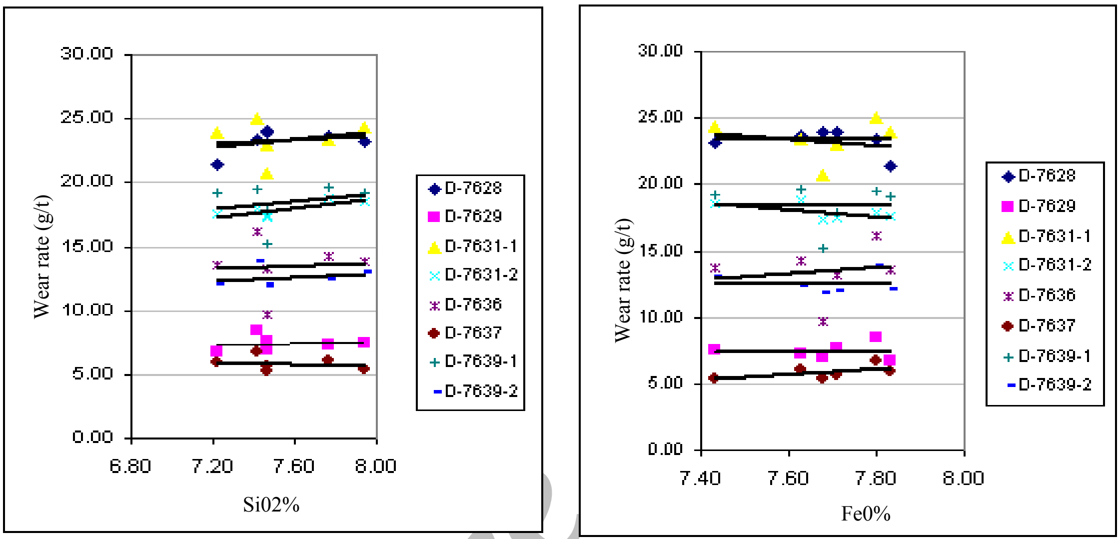


Fig. 10. Liner wear-ore composition correlation for Tabarestan Company products

Ravanshir Company: Segment R6 with a strong positive correlation of wear rate with FeO variations in the ore, had the following significant characteristics among other Ravanshir liner segments:

1. Contained the least amounts of Si% and Mn% (0.48 and 0.63 respectively), the average Si% was 0.58% and for Mn% it was 0.75%.
2. Has the least hardness (285 BHN) among other Ravanshir segments (ave.375 BHN).

The weakest relationship between wear rate and FeO% belonged to the segment R2 which had the following characteristics:

1. The least amounts of both Cr and Mo (1.99% and 0.28% respectively); the averages for Cr% and Mo% among Ravanshir products were 2.14% and 0.36 respectively.
2. In the laboratory analysis for wear rate determination (Pin on Disk method), this segment showed the highest wear rate (0.033 mm^3/Nm with average of 0.026 mm^3/Nm for the total Ravanshir samples).

The weakest relationship between wear rate and SiO_2% belonged to the sample R11 which had the following characteristics:

1. Contained the least amounts of carbon (0.43%) with the average 0.66% for all segments.
2. Contained the highest amounts of Si, Mn and Mo percentages (0.85%, 1.08% and 0.44% respectively); the averages for Si, Mn and Mo in Ravanshir products were 0.58%, 0.75% and 0.36% respectively.

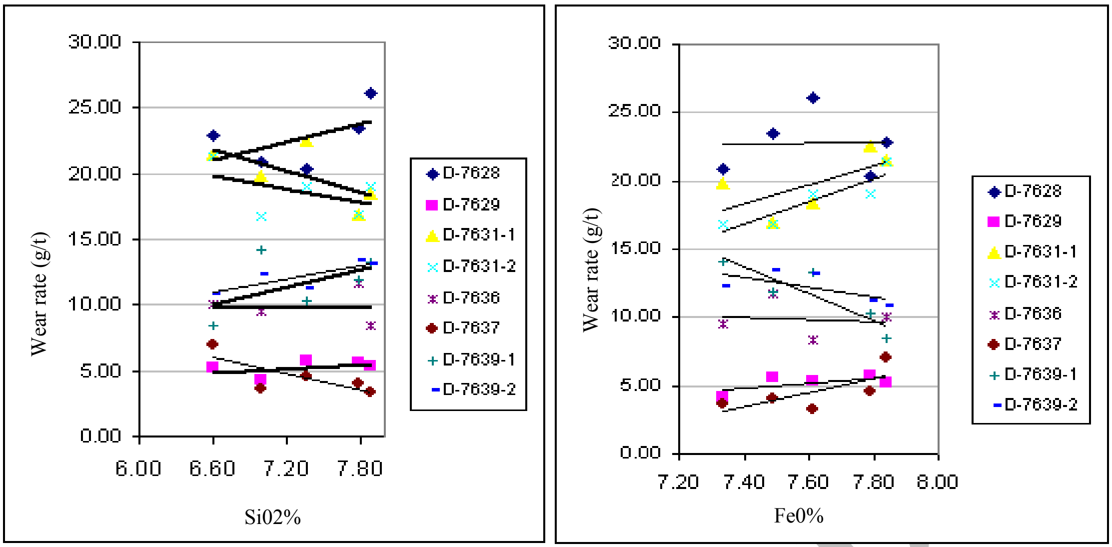


Fig. 11. Liner wear-ore composition correlation for Ravanshir Company products

Merat Poulad Company: In general Merat products presented greater sensitivity to the variations of FeO% (mostly a negative correlation) in the ore with respect to other companies, so it is in accordance with wear rate determination analyses which showed that Merat products were the least tolerant of wear. M3 had the strongest positive correlation of wear rate-SiO_2%, also the weakest relationship between wear rate and FeO% among other segments; it possessed the following characteristics:

1. Had the least hardness value (229 BHN) among other Merat liner segments (average: 375 BHN).
2. Showed the highest wear rate in "Pin on Disc method" (0.047 mm^3/Nm) among all other liner/lifter segments produced by the three companies.

M6 sample having the highest amounts of Ni (0.23%, Ave.0.15%) and the least amount of Mn (0.67%, Ave.0.78%) showed the greatest hardness (547 BHN); the weakest relationship between wear rate and SiO_2% belonged to this segment. The M13 sample with a relatively strong negative correlation between wear rate and FeO% variations had the least amount of Si (0.43% Ave.0.54%) among other Merat products.

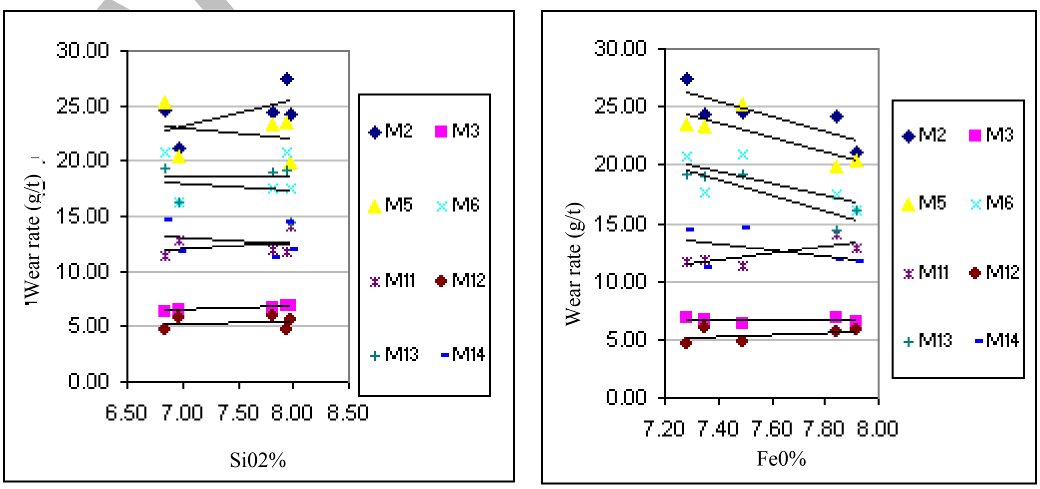


Fig. 12. Liner wear-ore composition correlation for Merat Poulad Company products

Table 8. Correlation data between liner wear and ore composition for the three liner producers

Tabarestan Steel Co.									
Wear – FeO Relationship									
Segment Code		**T2**	**T3**	**T5**	**T6**	**T11**	**T12**	**T13**	**T14**
r^2	No correlation or $r^2 < 0.1$		0.0012	0.0003		0.0224		0.0003	0.0036
	$0.1 \le r^2 < 0.5$	0.1280			0.3727		0.2926		
	$r^2 \ge 0.5$								
Type of Correlation	Positive + Negative(-)	(-)	+	+	(-)	+	+	(-)	(-)
Slope (Degrees)		67.59	8.23	10.83	69.30	65.88	63.43	11.68	18.00
Wear – SiO_2 Relationship									
r^2	No correlation or $r^2 < 0.1$		0.0178	0.0171		0.0072	0.0738	0.0508	0.0524
	$0.1 \le r^2 < 0.5$	0.1688							
	$r^2 \ge 0.5$				0.6549				
Type of Correlation	Positive + Negative(-)	+	+	+	+	+	(-)	+	+
Slope (Degrees)		56.36	16.68	36.73	62.15	34.35	28.46	55.71	33.64
Ravanshir Co.									
Wear – FeO Relationship									
Segment Code		R2	R3	R5	R6	R11	R12	R13	R14
r^2	No correlation or $r^2 < 0.1$	0.0003				0.0087			
	$0.1 \le r^2 < 0.5$		0.3574	0.4088					0.4801
	$r^2 \ge 0.5$				0.8055		0.5270	0.7777	
Type of Correlation	Positive + Negative(-)	+	+	+	+	(-)	+	(-)	(-)
Slope (Degrees)		10.65	59.97	81.75	82.96	30.94	78.88	84.10	75.09
Wear – SiO_2 Relationship									
r^2	No correlation or $r^2 < 0.1$					0.0007			
	$0.1 \le r^2 < 0.5$	0.2891	0.2360	0.4310	0.2288			0.2536	
	$r^2 \ge 0.5$						0.6558		0.5724
Type of Correlation	Positive + Negative(-)	+	+	(-)	(-)	+	(-)	+	+
Slope (Degrees)		66.08	28.45	69.87	59.00	3.36	63.93	64.85	59.41
Merat Poulad Co.									
Wear – FeO Relationship									
Segment Code		M2	M3	M5	M6	M11	M12	M13	M14
r^2	No correlation or $r^2 < 0.1$		0.0002						
	$0.1 \le r^2 < 0.5$						0.1944		0.2161
	$r^2 \ge 0.5$	0.6382		0.6545	0.5047	0.6313		0.7811	
Type of Correlation	Positive + Negative(-)	(-)	+	(-)	(-)	+	+	(-)	(-)
Slope (Degrees)		80.91	0.62	80.95	79.10	71.76	42.73	81.64	69.17
Wear – SiO_2 Relationship									
r^2	No correlation or $r^2 < 0.1$			0.0612	0.0004	0.0971	0.0238	0.0205	0.0575
	$0.1 \le r^2 < 0.5$	0.3429							
	$r^2 \ge 0.5$		0.8112						
Type of Correlation	Positive + Negative(-)	+	+	(-)	(-)	+	+	(-)	(-)
Slope (Degrees)		67.21	19.70	44.92	4.37	31.72	9.52	29.80	35.16

4. DISCUSSION AND CONCLUSION

Analyses of the mill feed composition and liner/lifter alloy structure confirmed the necessity of close control over these two important factors. It is worth mentioning that recent results about the correlation between wear and variations in ore composition do not present a general rule, firstly because it does not cover a sufficiently long enough time period, secondly other important factors such as grinding operational conditions are not considered. But from the correlations it is possible to judge the quality of liner material so that to justify perfomances of different liner/lifter products made by the suppliers. The most efficient way of evaluation of liner performance is to prevent other influent factors (mostly the operational conditions of the grinding mill) to vary during the determined period as much as it is amenable, and only then would it be possible to investigate the effects of ore characteristics on liner wear.

Heterogeneities exist (observed by metallographic tests) in the alloy structures of liners, mostly those made by the Merat Company. Consequently, such liner segments presented more sensitivity to variations of SiO_2% and FeO% contents in the iron ore. On the contrary, Tabarestan products, despite lower average values of Brinnell hardness, showed more uniformity in the alloy structure, which it seems has had a considerable effect on the weakened sensitivity of liners to the variations in ore composition. This brought better performance and longer life for Tabarestan liners in general. Ravanshir products generally showed the most variable, but the least values of wear rate, and also presented some strong correlations between wear rate and variations of SiO_2% and FeO%. Heat treatment that is sometimes applied (at an increased cost of the grinding media) has the overall effect of producing the desired microstructure. While it is well established that hard particles such as carbides greatly improve wear resistance, this is very much dependent on the characteristics of the matrix [5].

It should also be considered that one of the major causes of the shorter SAG mill runtimes in the processing lines where Ravanshir and Merat products were in use, was the critical liner segment (according to wear rate and wear ratio measurements) with its rapid wear rate and deformation, as it is well evident in Figs. 3 and 4 for segment No. 2. According to the degree of inclination of the correlation lines (given as slope in Table 1), it would be possible to give a measure of sensitivity of liner wear to the variations of either silica or ferrous oxide. As previously mentioned, it was not the subject of this research to investigate other sources of liner wear such as the behavior of the mill load and impacts of steel balls, as well as electrochemical phenomena. However, one thing that was realized through the whole research was the different ways hematite and magnetite (two major constituents of almost all iron ores) participate in media wear in grinding mills, especially AG/SAG mills. Magnetite, with a greater abrasion index than hematite, also in finer particles, is responsible for additional wear rate (abrasion) in liners, but hematite with greater toughness/grindability (work index) exists in the mill with larger particle sizes, thus it could produce wear on liner parts with less tolerance to impact as is the situation for martensitic steels. According to a recent study on the comparison of the simulated particle size distributions of the circuit streams with variations in feed ore, changes in ore hardness have less of an influence than particle size properties [6]. Moreover, further investigations such as measurements of abrasion index and more metallurgical proof are necessary for a confident conclusion; perhaps in this way one would be able to find a reasonable answer to different trends (positive or negative) in the discussed variations for individual liner segments.

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