RAHUL SINHA
A. K. MUKHOPADHYAY
and
SATYA PRAKASH

Roll crusher liner wear investigation and experimental study

Wear on the surface of the rolls of the roll crusher is very common during crushing. The wear zones on the rolls have been identified as sliding zone and compression. In the present study wear in sliding zone has been investigated using the damaged liner of the rolls. The study was carried out to identify the wear mechanisms obtained on the rolls. To correlate the wear mechanisms obtained in sliding zone, dry sliding abrasive wear experiments has been processed further. The dry sliding abrasive wear experiments were also used to find out the weight loss. This was performed using statistical modelling to identify the effects of wear parameters on weight loss. The obtained results of equation in statistical modelling confirmed the validity of the wear model. The surface of the test samples was examined under field emission scanning electron microscope to validate the results of wear mechanisms of liners.

Keywords: *Crusher, liner wear characterization, statistical modelling, analysis of variance, regression modelling.*

1.0 Introduction

The roll crusher liner is mostly attracted towards the wear in terms of surface damage results in weight loss. The damage on liner surface is attributed to material of construction, service variables wear process etc. The resistance against wear depends on material of construction due to abrasive wear process which therefore results in microstructural changes [1].

Abrasive wear arises due to sliding movement of hard particles along moving surfaces. At different surface zones of roll crusher, wear mechanism is different. There are two different wear surface zones developed during crushing of feed materials. One is sliding zone at the beginning of crushing and another one is compression zone during crushing of feed materials. In sliding zone the feed materials and the rolls act as two-body and the wear mechanism is two-body wear mechanism. Whereas, three-body wear mechanism develops during proper nipping of feed materials and crushing of feed materials. In three-body abrasion, particles are free to roll or slide in the interface between two moving surfaces. These particles when travelling from one position to another on roll surface creates damages on the surface of the rolls. The particles cause scratches and repeated indentation on the surface of contact. Crushing operation in a double roll crusher is an example of three-body combination, where the two rolls and the feed material form a three-body combination. Very little has been reported so far about the wear on roll crusher liner due to three-body abrasion mechanism. Three-body abrasive wear behaviour of various polyaryletherketone composites have been carried out under different loads and sliding distances by using pin-on-disc machine and a rubber wheel abrasion test [2]. The abrasive wear performance has been correlated with mechanical properties. The condition of worn surfaces under three-body abrasion was examined to study on the abrasive behaviour of randomly oriented glass fibre reinforced with epoxy resin field Al_2O_3, SiC and pine bark dust [3]. It was observed that the material was more sensitive to variations of abrading distance and less sensitive to sliding velocity. Abrasion resistant of phenol formaldehyde based composite break pad material under the influence of abrading distance and load on three-body abrasive wear behaviour was examined by Manoharan et al. [4].

The worn surfaces were examined by scanning electron microscopy (SEM). Results indicated that the wear volume loss increases with abrading distance and load. The abrasive wear of materials with different hardness have been reported in which it was found that the abrasion rates and wear coefficient do not vary much with changes in hardness [5]. The worn surface features were examined through scanning electron microscopy to probe the wear mechanism of carbon fabric reinforced epoxy (C-E) composite [6]. Taguchi multi response method was applied in this study to optimize the three-body abrasive wear. Other than hardness it is considered that material brittleness, microstructural properties and microstructural phase change may result changes in wear behaviour [7]. Sesemann et al. [8] performed a laboratory test on high pressure grinding rolls to identify wear system depending on grinding pressure, grain size and moisture in feed materials. The wear resistant material used for the test

---

Messrs. Rahul Sinha, A. K. Mukhopadhyay and Satya Prakash, Dept. of Mining Machinery Enginering, Indian School of Mines, Dhanbad, India. Corresponding author: Rahul Sinha E-mail: rahulsinha@mme.ism.ac.in

was martensitic hardened steel AISI L6. They explained that the control of indentation mechanism is dependent on the roll gap and the pressure. Grain size distribution of feed material affects grinding pressure which results in high stress for large grains. This process increases wear rate. The wear rate is also affected by moisture content as described by them in their work. Further investigation was done under SEM to identify wear mechanisms. It was concluded that abrasion grooves with surface micro-cracks are the main causes of material loss. In some parts of wear resistant material it has been identified that micro-fatigue of repeated indentation subjugate the wear operation. In order to understand abrasive wear behaviour under high-stress and low-stress condition, a test was conducted between mild steel specimen and rubber wheel [9]. The abrasive particle size ranges between 125-150 µm and 425-500 µm. Wear mechanism on mild steel specimen involves surface deformation due to indentation by the abrasive particles under three-body wear test conditions. A relation was established to find out the transition to the formation of grooves under three-body abrasion. Ting sun et al. [10] examined the wear behaviour of bainite ductile cast iron at three different loading conditions. The material was worked and cooled at constant temperature of 20ºC with finer microstructure and superior mechanical properties showed better wear resistant property. The worn surfaces were analyzed under SEM and X-ray diffraction (XRD). Yao and Page [11] studied the worn surfaces of high pressure shear cell (HPSC) using optical, contact profilometer, confocal and scanning electron microscopy to find the effect of overall particle size distribution on wear in the crushing zone. The acoustic emission (AE) signal caused by friction during sliding motion on surface deformation was studied by Alam Hase et al. [12].

In the field of mining industries, minimum number of literatures focused on abrasive wear problems of roll crusher liner surface during crushing or nipping of feed particles. However, none of the work has been done so far on study of abrasive wear in sliding zone of rolls surface of the roll crusher. In this study, the work was carried out to discuss about surface damages observed on the roll liners surface. To establish the relation of wear in sliding zone on liner surface of the roll crusher, experiments using pin-on-disc tribometer was performed. Also, statistical approach towards solving the issue of material losses from roll crusher liner surface has been done in this paper. Investigations of liner wear will benefit in improving the crusher performance, reduction in down time and uniform product size distribution. To perform this task, samples of Mn-steel liner material were collected from mines. Microscopic investigations on Mn-steel liner samples were performed to investigate wear characterization. In order to investigate and validate the microscopic results of abrasive wear in sliding zone, abrasive wear experiments using pin-on-disc tribometer was used. To perform this test pin samples were fabricated as per ASTM G99 standard of abrasive wear experiment. For this experiment, compositions of pin samples were made same as that of roll crusher liner. Validation of microscopic results was made using field emission scanning electron microscope (FESEM). This technique will be useful to understand the wear mechanisms on roll crusher liner surface by comparing the wear characterization on the surface of pin materials used for the abrasive wear experiment. Also, comparisons between the effect of load applied, speed, sliding distance and hardness of the material were done based on abrasive wear experiments. The abrasive wear experiments performed in this study by using pin-on-disc tribometer were based on design of experiment (DOE). The experiments were designed by selecting two levels of factor for wear parameters. The selected levels were low level and high level. Whereas, the selected parameters for abrasive wear experiments were load, speed, sliding distance and hardness of prepared pin samples. The pin material for the abrasive wear experiment was fabricated from Mn-steel liner sample. Whereas, the discs were coated with thick layer of coal bed with 600 mesh size of coal to run the experiment based on full factorial design. ANOVA table was obtained to find out the relevant parameters for weight loss. If the obtained p-value in ANOVA table comes out of less than 5% level of significance then the parameter would be in consideration for the minimizing or maximizing of weight loss. The regression equation was developed to understand the cause of weight loss from pin sample. Validation of regression equation was done on the basis of predicted and measured weight loss of material.

2.0 Roll crusher liners

Liners in roll crusher are used in many forms. They may be smooth, corrugated or toothed type. The present work considers smooth type liners. The loss of liner material mainly occurs in the form of wear. Wear is insidious and universal in occurrence. The need for selection of suitable liner materials is becoming justified in view of increased cost per tonne of coal handling.

2.1 INFLUENCE OF CHEMICAL ELEMENTS

Wear in liner is a function of alloy composition, rock properties, machine operating parameters and host of other factors. Austenitic manganese steel liner develops work hardening property under stress, can withstand extreme impact without fracture. Low carbon molybdenum steel with hardness value between 300-370 BHN has excellent wear resistant characteristics capable of withstanding impact. High carbon chrome molybdenum steel (325-380BHN) is also used as a liner material with variations in carbon and chrome content. NIHARD iron (550 BHN) is used where impacts are low and capable of handling abrasive types of rock. High chrome irons (>600BHN) is considered to have superior wear abrasion characteristics but brittle than chrome molybdenum white iron whose hardness ranges between 600 to 700 BHN which possess abrasion resistant property. Manganese steel

Table 1: Composition of different liner materials

Material	Compositions						
NIHARD 4	C%	Mn%	S%	Si%	P%	Cr%	Ni%
	2.80-3.00	0.5	≤0.05	1.90	≤0.07	8.50	5.50
High carbon chrome-Mo steel	C%	Mn%	S%	Si%	P%	Cr%	Mo%
	0.380-0.43	0.75-1.10	≤0.04	0.15-0.30	0.09	0.08- 1.10	0.15-0.25
Mn-Cr steel	C%	Mn%	S%	Si%	P%	Cr%	Mo%
	0.55-0.70	0.50-1.00	0.05	0.75	0.05	1.00	0.20

was invented by Sir Robert Hadfield in 1882 which possess excellent toughness, ductility and work hardening property. For rock crusher liner, the composition of carbon is around 1%, manganese 11% and the balanced is iron (Fe). It is found to be the best for crushing rocks with high compressive strength. Increase in carbon and manganese level change material properties which improves wear life while crushing lower compressive strength rock but reduces the fatigue strength of the material. Presence of excess chromium have adverse impact on wear liner fatigue properties in high impact applications. High carbon-manganese percentages give the best result compared to standard manganese when crushing lower compressive strength and high silica content rocks. As the carbon level increases, the manganese content also to be increased to retain sufficient fatigue strength. High hardness, high strength and good toughness are the requirement of durable liners. The compositions of liners used in mining industries under different operating conditions are described in Table 1. Uneven wear profile of liner affects product dimension [13]. It is reported that the feed material properties, operational parameters and material properties of liners have considerable effect on uneven wear. Liner performance can be improved by keeping balance content of required material compositions. Carbon content determines the volume content of carbides which increases hardness and improves strength. The presence of silicon effects fracture resistance properties with increase in its content. For achieving good toughness and corrosion resistant property, low silicon together with increased chromium and nickel delivers good result. Nickel-chromium combination improves hardenability, increase strength and toughness by forming eutectic carbides. The nickel content above desired level affects hardenability property. Sometimes, molybdenum is used to achieve good hardenability, creep strength, hot hardness, corrosion and wear resistant properties. To mitigate the brittleness of the material due to presence of sulphur, manganese is used. Manganese steel used as liner in crushing equipment is a cast material followed by heat treatment after initial cooling. The material is heated up to 1000ºC to convert the brittle multiphase microstructure to a single phase austenite followed by rapid water quenching. The single phase austenitic microstructure gives a high strength ductile material resistant to fatigue. The material causes work hardening property and the Brinnel hardness may rise from initial value 200 to 500 and above. With carbon above 1% and manganese above 11% it is considered the best material for crushing high compressive strength rock. Material property gets changed by increasing carbon and manganese percentage which is found suitable for crushing low compressive strength rock with excellent wear resistant property. Carbon is the main constituent that determines the life of the liner against wear.

3.0 Results and discussions

3.1 FESEM investigation on worn surface of liner

The liner material in use in coal handling plant was Mn-steel of grade I compositions (as described in Table 2). To proceed with the characterisation of abrasive wear on the damaged surface of liner, part of liner sample was collected from different surface zones of the roll. In order to distinguish wear characterisation, field emission scanning electron microscopy (FESEM) has been used here to investigate the category of wear on liner material. The surface texture indicates the type of wear takes place in crushing operation. The sample of liner, a Mn-steel wear resistant material, was collected from a mineral processing plant, which was cleaned with acetone for examining purpose under field emission scanning electron microscope (FESEM). The composition of this liner sample is given in Table 2.

Table 2: Composition of liner sample under study

Material	Compositions				
Mn-steel	C %	S%	Mn%	Si%	P%
	1.05-1.35	1.00	11.00-14.00	0.05	0.09

FESEM images obtained were examined to analyse microstructural characteristics, such as, presence of indentations, formation of flakes, growth of micro-cracks and plastic deformation. SEM micrographs are shown in Fig.1.

Fig.1 (a) shows surface damage in terms of ploughing and presence of cracks. Fig.1(b) shows formation of flakes. Flakes cause a potential weakness and affect wear resistant property of the material. Fig.1(c) confirms that under the attack of feed material, the individual particle penetrates deeply into the surface of the liner causing formation of cavities. Fig.1(d) and Fig.1(e) shows formation and growth of micro-cracks with presence of voids. The worn out surface consists of copious ductile dimples in the form voids, also exhibits intergranular wear and presence of relatively shallow ductile dimples. This reduces the bonding between the particles and the matrix,

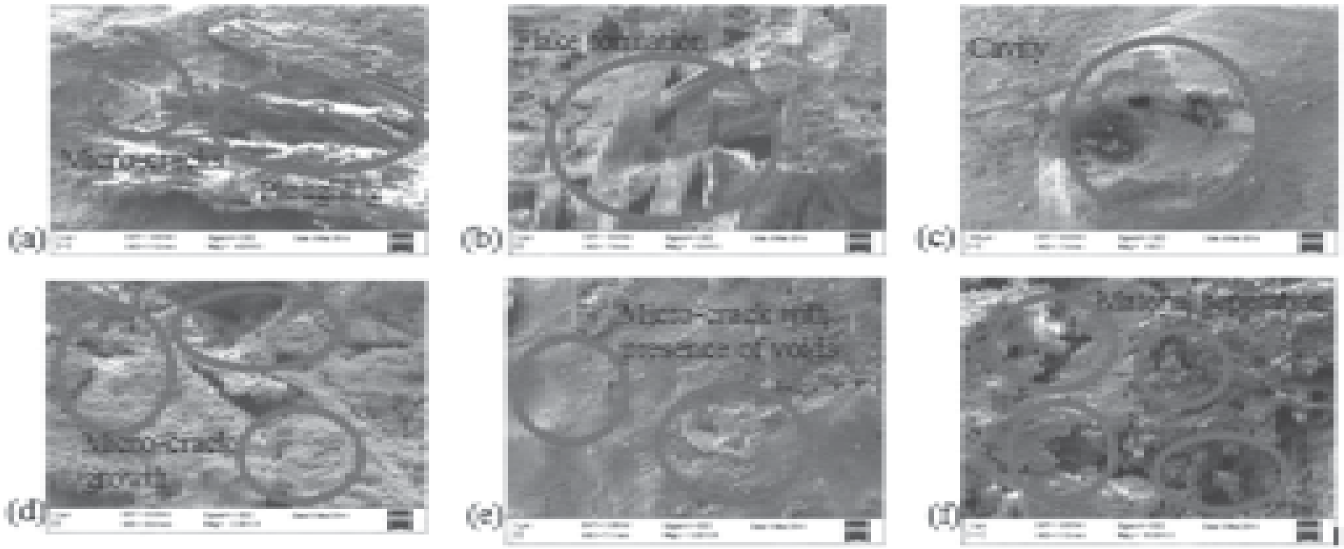


Fig.1 Scanning electron microscope micrographs of the sample under study

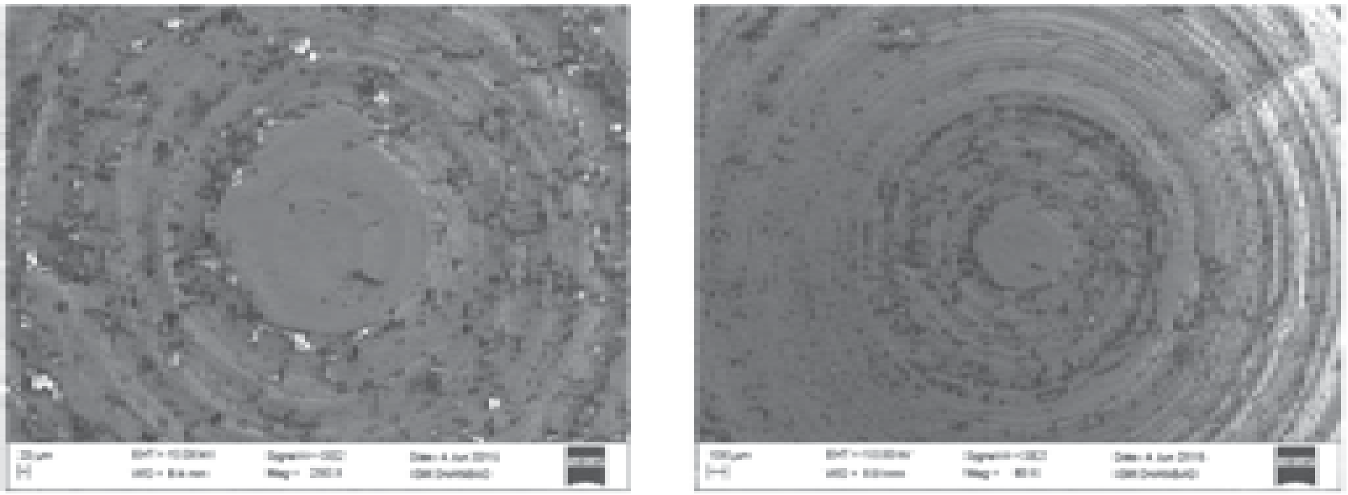


Fig.2 Microphotographs of pin samples before abrasive wear experiment under pin-on-disc tribometer

which in term allows micro-void coalescence and promotes wear. Fig.1(f) shows severe damage on liner surface in the form of cracks, voids and material separation.

3.2 Experimental procedure

To validate the microscopic results obtained for roll crusher liner for abrasive wear characterization, pin-on-disc tribometer was employed. To perform this work, worn out liners from mines survey was collected for abrasive wear characterization. Further work was carried out to fabricate the Mn-steel liner samples with two different hardness values, 250 BHN and 350 BHN, by keeping the same composition as that of Mn-steel liner. The shape of pin samples for pin-on-disc abrasive wear experiments were then made according to ASTM: G99 standard.

To run the abrasive wear experiments successfully, 30 numbers of pin materials were fabricated to a dimension of 30 mm of length with 10 mm of diameter. 15 pin samples were made of 250 BHN hardness value and other 15 pin samples were made with hardness value of 350 BHN as per the requirement for experimental work. The microscopic images for the material were taken before performing experiments as shown in Fig.2. The pins were made to run on circular rotating type metallic disc coated with a layer of thick coal bed having 600 mesh size of coal. The metallic discs were of circular rotating type having diameter of 140 mm and 12 mm thickness.

For every test run the pin samples under wear consideration were properly metallographically polished. It was then fixed with the pin holder, a body part of the pin-on-disc tribometer, and its end surface was contracted with the coal layers on the metallic disc. The disc was then rotated at a fixed speed with the load provided on the pin samples. The load was applied through cantilever mechanism. For each test to be conducted new layers of coal bed on the disc was used at different run diameter on the disc. The pin samples were washed with acetone to perform each test before and after each runs. It was then weighed using electronic balance having sensitivity accuracy of ±0.01 gm. For an average of 5 tests were conducted for every test condition.

3.3 Design of experiment (DOE)

The plan order of present work for abrasive wear experiments were based on DOE technique. This helps in performing a task for parameter analysis using analysis of variance (ANOVA) technique. The factors chosen for the analysis purpose were load, speed, sliding distance and hardness of the Mn-steel material. Works were done under DOE with two levels, i.e. low (–) and high (+), which accordingly 24 experiments were conducted based on 'Pn' relation as shown in Table 3. The experiment was conducted with an aim to model the consequence of abrasive wear parameters on weight loss of the material.

Table 3: Selected level of factors of pin-on-disc experimental work

Parameters	Unit	Levels	
		a	b
Load	N	10	20
Speed	rpm	100	300
Sliding distance	m	780	1500
Hardness	BHN	250	350

3.4 Regression analysis and statistical modelling

The selected parameters like load (N), speed (rpm), sliding distance (m) and hardness (BHN) were used to study weight loss (mg). The methodology of the model was accomplished using Design Expert 9.0.6 software [14]. To correlate the wear parameters with each response it becomes important to develop regression equation. In this respect to confirm the validity of the regression model new test were conducted. In this test the value close to the low and high level were taken from Table 4.

Table 4: Experimental results of full factorial design for abrasive wear test

Levels				Weight loss (gm)
Load (N)	Speed (rpm) (m)	Sliding distance	Hardness (BHN)	
–	–	–	–	0.003
+	–	–	–	0.025
–	+	–	–	0.007
+	+	–	–	0.023
–	–	+	–	0.006
+	–	+	–	0.032
–	+	+	–	0.006
+	+	+	–	0.026
–	–	–	+	0.009
+	–	–	+	0.041
–	+	–	+	0.017
+	+	–	+	0.035
–	–	+	+	0.004
+	–	+	+	0.019
–	+	+	+	0.018
+	+	+	+	0.047

3.5 Analysis of the design of experiment (DOE) for abrasive wear tests

With the help of ANOVA the abrasive wear tests result were analysed to scrutinize the effect of wear parameters (load, speed, sliding distance and hardness). The result in ANOVA helps in identifying the percentage contribution of each parameter and their interactions on the weight loss (gm) as response. The results were calculated at 95% confidence level. If p-value is less than 0.05 it then signifies that the parameter(s) have statistically significant benefaction over the response, in this case is the weight loss in 'gm', otherwise not.

3.6 Validation of result using analysis of variance and surface plot

3.6.1 Analysis of variance for weight loss (gm)

From the column of p-value in ANOVA table for weight loss (gm), (Table 5), it was found that the p value for the load and hardness are less than 0.05. Also, interactions of 'speed and hardness' is less than 0.05. This provides information on the significant contribution of the parameters towards weight loss. Whereas, other parameters like sliding distance, hardness, load × hardness and sliding distance × hardness doesn't have significant contribution towards weight loss.

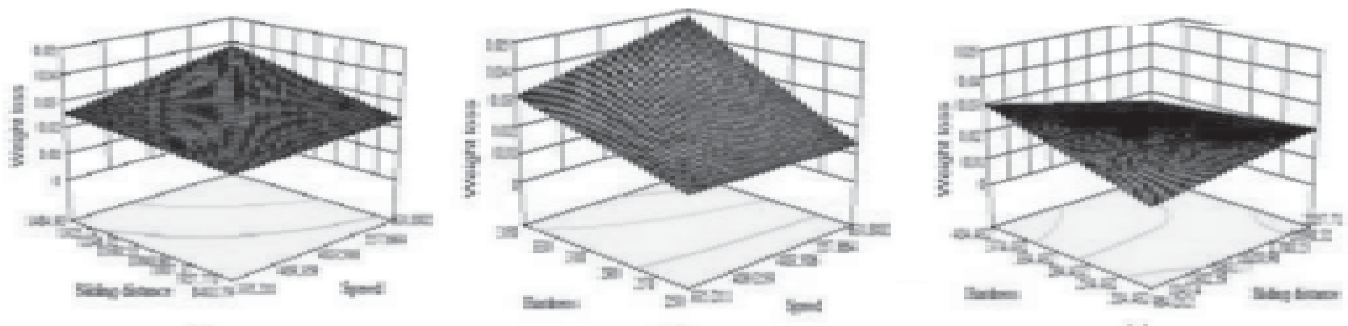
Table 5: ANOVA for weight loss (mg)

Source	p-value
Model	0.0006
A-load	0.0001
B-speed	0.0567
C-sliding distance	0.9125
D-hardness	0.0096
BC	0.1110
BD	0.0291
CD	0.1820
BCD	0.0291

R-squared = 95.27%, R-squared (adj) = 89.87%

3.6.2 Analysis of weight loss using surface plot

The dependency of load, speed, sliding distance and hardness has been presented in Fig.3. Fig.3 represents effect of contour plot and surface plot in two different planes. From Fig.3(a) it can be identified that with the increase in speed, weight loss increases to great extent whereas sliding distance has less significant contribution towards weight loss. Fig.3(b) shows that speed and hardness has significant contribution towards weight loss. In Fig.3(c) it can be concluded that sliding distance and hardness together contributes in minimising weight loss of the material. Therefore, there is no significant contribution of sliding distance on weight loss.



(a) (b) (c)

Fig.3 Surface effect plot on the basis of contour plot for observation of: (a) Speed and sliding distance against weight loss, (b) speed and hardness against weight loss and (c) sliding distance and hardness against weight loss

3.6.3 Analysis of weight loss with regression equation

For analysis of weight loss, regression equation developed with the help of ANOVA through adjusted SS (sum of squares). The regression equation was developed based on the effects of individual wear parameters and their interaction's which is expressed below:

$$\text{Weight loss (gm)} = 0.002 + 0.000001869 \times \text{load} + 0.000000211956 \times \text{hardness} + 0.000000137964 \times \text{speed} \times \text{hardness}$$

From the developed regression the positive sign in the equation shows increase in weight loss with respected parameter. Weightage of each parameter is defined by its magnitude represented. Above equation informs that load gives major contribution in maximizing weight loss. Hardness and interaction of hardness with the speed has less contribution towards weight loss. This can be concluded that in order to improve the weight loss to a minimal amount the two parameters should be taken into consideration i.e., load, speed and hardness. Hardness of material depends on metallurgical properties of material. With the increase in load there is increase in area of contact of surface asperities between the two bodies. Also, increase in load increases depth of penetration of harder surface asperities of one body into another body which results in material loss from the surface of one material during abrasion process. With respect to the above line it can be briefly explained that during abrasion process there is increase in temperature at the contact surface. This softens the surface asperities in contact, results in weak bonding at the contact surface. This weak bonding abraded away during abrasion process which not only decreases height of surface asperities but also increases depth of penetration at the contact surface. Therefore, more chances of loss of material. However, harder the material there is less chance of surface asperities penetration into another. But this increase in hardness affects the mechanical properties which results in compromise in metallurgical properties of material [15].

3.6.4 Validation of regression equation

In order to validate the regression equation with the measured value of weight loss, two confirmation tests were performed as shown in Tables 6 and 7. One of the confirmation tests for validation of regression equation, as shown in Table 6, were performed at two selected parts (i.e. Part-A and Part-B). In Part-A of Table 6, the % error in obtained results varies from 2.84% to 9.62%. Whereas, % error results obtained in Part-B of Table 6 varies from 2.28% to 17.30%. Another confirmation tests were run at ascending

TABLE 6: CONFIRMATION TEST WITH THE REGRESSION EQUATION

Run order	Load (N)	Speed (rpm)	Sliding distance (m)	Hardness (BHN)	Weight loss (gm)	Weight loss (gm) [predicted]	% error
			Predicted and measured result of part A experiment				
1	5	150	900	250	0.0101	0.00723	2.84
2	25	250	1800	350	0.0157	0.01419	9.62
3	5	250	1800	350	0.0156	0.01415	9.29
4	25	150	900	250	0.0068	0.00727	-6.91
			Predicted and measured result of part B experiment				
1	15	200	1200	250	0.0096	0.00897	6.56
2	25	350	1800	350	0.023	0.01902	17.3
3	15	350	1800	350	0.017	0.01900	-11.76
4	25	200	1200	250	0.0092	0.00899	2.28

TABLE 7: SECOND CONFIRMATION TEST FOR MEASURED AND PREDICTED VALUE OF WEIGHT LOSS

	Load (N)	Speed (rpm)	Hardness (BHN)	Measured: weight loss (gm)	Predicted: weight loss (gm)	% error
1	5	90	250	0.0038	0.005166	-35.94
2	10	120	350	0.0066	0.007880	-19.39
3	15	150	250	0.0101	0.010030	6.93
4	20	180	350	0.0092	0.010800	-17.39
5	25	210	250	0.0091	0.009340	-2.63
6	30	240	350	0.0033	0.003289	0.33

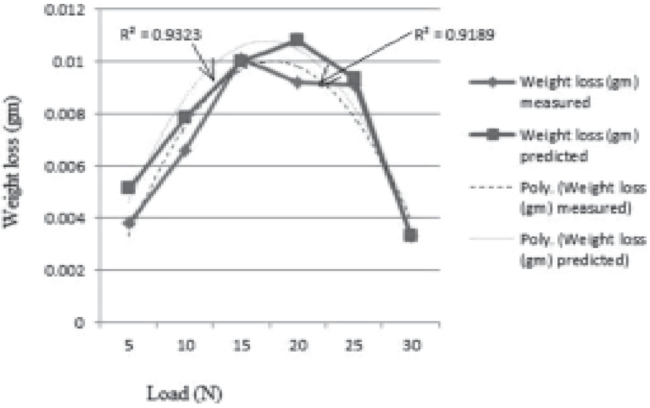


Fig.4 Graph plot for load and weight loss for measured value from experiments and predicted value obtained from regression equation

order of load (N) and speed (rpm) as shown in Table 7. In Table 7, effect of load and speed were selected with respect to the hardness of material. Graph was plotted against load (N) and weight loss (gm): measured and predicted. The plotted graph is shown in Fig.4. From the derived regression equation as the magnitude of load is higher considering its effect in weight loss. The obtained results of R^2, as obtained in the plotted Fig.4, for measured and predicted plots are 0.9189 and 0.9323 respectively. The results obtained were proved to be more beneficial in minimising weight loss. Thus, the derived regression equation correlates with the wear assessment of Mn-steel material at some approximation level.

3.7 Validation of microscopic image obtained using pin-on-disc tribometer under FESEM

The pin-on-disc abrasive wear experiments were done to perform three-body abrasive wear tests. The three-body wear occurs when any two bodies are separated by other matters and is passing through it. In this experiment it was found that plowing, micro-cracks, micro-scratch with some amount of cavities has been developed. These surface formed defects remove the surface material in the form of weight loss or material loss. The results of microphotograph under FESEM are shown in Fig.5. In Fig.5(a), ploughing has been observed with micro-scratch on the surface of Mn-steel material. As the abrasive medium used in this experiment case was coal. Along with plowing, as shown in Fig.5(a) and 5(b), microphotographs of cavities and micro-cracks were also found as shown in Fig.5(c) and 5(d). The hardness of the Mn-steel sample materials in use for experiment purpose is observed to be increasing after each abrasive wear test. It was found that hardness play an important role in decreasing the material loss from the surface material when load is increased to some amount.

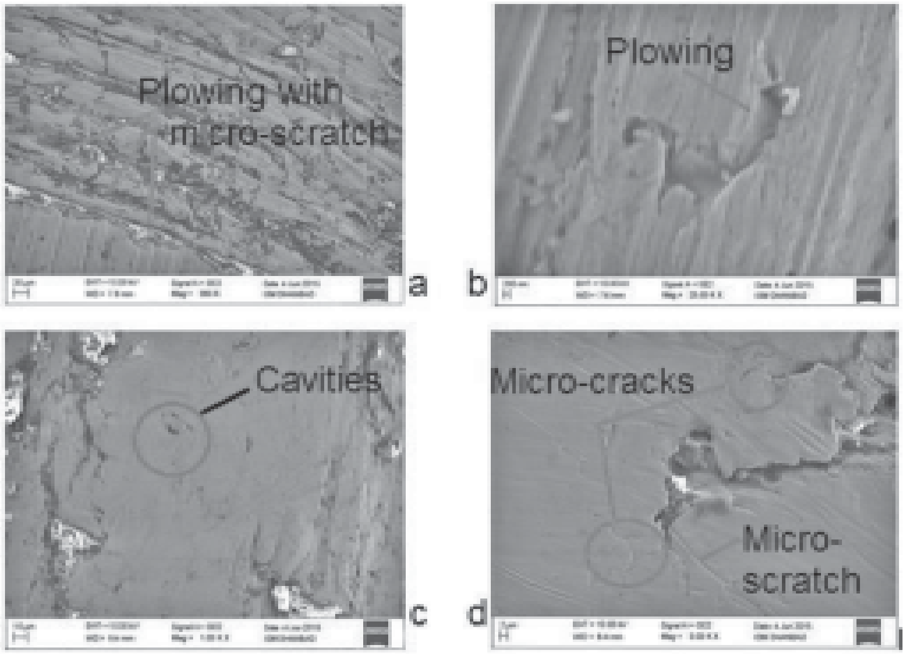


Fig.5 Worn surface microphotographs of Mn-steel pin samples under pin-on-disc tribometer

4.0 Conclusions

Field emission scanning electron microscope (FESEM) was used to validate the microscopic image of worn out Mn-steel liner sample with the worn out pin samples fabricated for abrasive wear experiments. This technique helps in building a bridge between two models i.e. field data observation of roll crusher Mn-steel liner with the experimental observation of fabricated Mn-steel pin samples. The abrasive wear experiments were proposed using design of experiment (DOE). The analysis of variance (ANOVA) results obtained through DOE satisfies the condition of weight loss from both field data observation to experimental data observation. The results of p-value shows load is the dominating cause of weight loss. Whereas, speed and hardness plays their important role other than load to cause wear. The regression equation developed using ANOVA was validated by a number of confirmation tests. Graph was plotted against load and measured and predicted values of weight loss. In the plotted graph for load and out variable as weight loss the value of R^2 was obtained as 0.9189 and 0.9323 for measured and predicted value of weight loss respectively. This confirmation test suits the regression equation with permissible value of % error for measured and predicted weight loss. The steps used in this study observed to be most suitable for mining industries.

References

1. Walker, Simon (2012): "Beating crusher wear challenges; developments in the metallurgy of crusher wear parts are helping operators reduce the impact of wear on their operations; Crushers," *E&MJ Engineering and Mining Journal*, 17 May, pp. 54-56.
2. Harsha, A. P. and Tewari, U. S. (2003): "Two-body and three-body abrasive wear behaviour of polyaryletherketone composites," *Polymer Testing* 22; pp 403-418.
3. Patnaik, Amar, Satpathy, Alok and Biswas, Sandhyarain (2010): *Malaysian Polymer Journal*; Vol 5; No. 2; pp 37-48.
4. Manoharan, S., Swesha, B., Bharath, P. B. and Ramadoss, G. (2014): "Investigations on three-body abrasive wear behaviour of composite brake pad materials;" *Plastic and Polymer Technology (PAPT)*; Vol 3.
5. Das Bakshi, S., Shipway, P. H. and Bhadeshia, H. K. D. H. (2013): *Wear* 308; pp 46-53.
6. Subbaya, K. M., Rajendra, N., Varadarajan, Y. S. and Suresha, B. (2012): "Multiple Response Optimization of three-body abrasive wear behaviour of graphite filled carbon-epoxy composites using grey-based taguchi approach;" *Journal of Minerals and Materials characterisation and engineering*; 11; 876-884.
7. Bourithis, L. and Papadimitriou, G. (2005): "Three body abrasion wear of low carbon steel modified surfaces," *Wear* 258, 1775–1786.
8. Sesemann, Y., Broeckmann, C. and Ofter, A. H. (2013): "A new laboratory test for the estimation of wear in high pressure grinding rolls," *Wear* 302, 1088-1097.
9. Dube, N. B. and Hutchings, I. M. (1999): "Influence of particle fracture in the high-stress and low-stress abrasive wear of steel," *Wear* 233–235, 246–256.
10. Ting, Sun, Ren-bo, Song, Fu-qiang, Yang, and Chun-jing, Wu (2014): "Wear behaviour of bainite ductile cast iron under impact load," *International Journal of Minerals, Metallurgy and Materials*, Volume 21, Number 9, 2014, Page 871.
11. Yao, M. and Page, N. W. (2000): "Influence of comminution products on abrasive wear during high pressure crushing," *Wear* 242, 105–113.
12. Alan, Hase, Masaki, Wada and Hiroshi, Mishina (2014): "Scanning electron microscope observation study for identification of wear mechanism using acoustic emission technique," *Tribology International* 72, 51-57.
13. Oberheuser, G. (1996): "Wear protection of surfaces from high pressure grinding rolls: possibilities and limits," *Int. J. Miner. Process*, 44-45, 561-568.
14. Stat-Ease Inc. (2014): Handbook for experiments of Stat-Ease statistical software, 2021 East Hennepin Ave, Suite 480 Minneapolis, MN 55413.
15. Haizhi, Y. (2003): "An overview of the development of Al-Si-alloy based material for engine applications," *J. Mater Eng Perform*, 12:288-97.