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INFLUENCE OF PARTICLE SIZE AND LOAD ON LOSS OF MATERIAL IN MANGANESE-STEEL MATERIAL: AN EXPERIMENTAL INVESTIGATION

The present study explores the influence of variables like particle size of coal, load, speed and sliding distance on weight loss in manganese-steel (Mn-steel). The observations are made using pin-on-disc apparatus. Specimen prepared from Mn-steel used for the wear test. The size and shape of specimen is in accordance with ASTM G99 standard. From design of experiment (DOE) procedure the variables load were altered to assess the weight loss in material. It is observed that with the increase in particle size and load, the weight loss increases when other variables are constant. Mn-steel shows decrease in weight loss at higher load due to property of dipole interaction and stacking fault energy (SFE). Decrease in weight loss at higher load results in transition in wear mechanism from scratch to groove formation as observed under field emission scanning electron microscope (FESEM).

Keywords: Mn-steel, abrasive wear, stacking fault energy, FESEM, DOE

1. Introduction

Mn-steel is widely used as liner material in different material handling equipment to protect the crusher from severe damages. Sinha et al. [1] describes the wear phenomena on Mn-steel liner due to sliding abrasion. They observed that material loss from Mn-steel surface takes place due to sliding of abrasive particles and application of load. Thereby they describe the principles of wear through sliding abrasion. Acselrad et al. [2] on abrasive wear investigation of 10wt.% Mn-steel, the wear rate of 10wt % Mn-steel varies with the application of load but has indirect effect with the increase in sliding distance. Application of load on Mn-steel results in change in mechanical property. The mechanical property of Mn-steel depends on dipole interaction of C-Mn and stacking fault energy (SFE) which leads to increase in strain hardenability as observed in pin-on-disc abrasive wear test on abrasivity of rock and other material [3]. The present study elucidates the influence of load and particle size on weight loss of Mn-steel with coal particles experimentally supported by theory. Types of wear have been identified using FESEM. Finally it is concluded that the loss of weight due to wear on liner material is proportional to the load but increases with the increase in particle size of coal. Also, a model has been developed using design of experiment (DOE) technique to find out the weight loss in liner due to wear and then compared with the experimental observations. From DOE, ANOVA is used to find out the dominating factor between the load and particle size.

2. The specimen

A specimen has been prepared from manganese-steel (Mn-steel) liner material of a crusher used for sizing coal. The specimen was prepared in accordance to ASTM G99 standard. The shape of the specimen is pin type with the dimensions is shown in Fig. 1. At first the specimen was metallographically polished to remove oxide contents. Surface polishing of the pin was done to bring the surface roughness to the approximate level of 0.40 μm which was verified by surface profilometer. The test specimen was then heated in an oven to make it free from moisture. The prepared specimen has been used to determine the weight loss under the influence of load and size of coal particles.

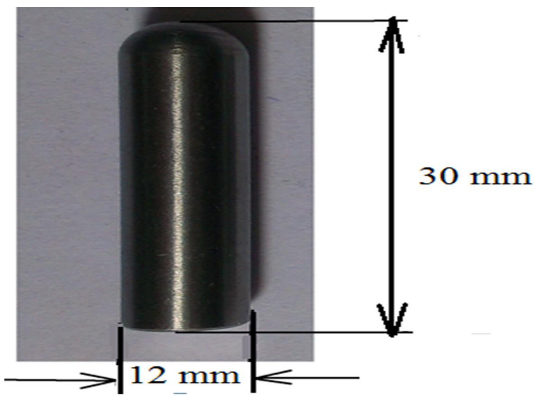

Fig. 1. Test specimen prepared as per ASTM G99 standard

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3. The size of coal

Two sizes, 500 µm and 710 µm, were considered for investigating into the weight loss of liner material. The finer sizes of coal have been considered as the amount of weight loss driven more than finer size particle. The sizes were sorted out using sieve analysis technique. At first coal samples were taken and put on a sieve having mesh size 500 µm and 710 µm separately. The sieve was then shaken and the undersized particles collected were of either 500 µm or 710 µm based on the sieve sizes.

4. Experimental set-up: pin-on-disc apparatus

For investigating weight loss experimentally pin-on-disc apparatus is used in this study and is shown in Fig. 2. In pin-on-disc tribo-setup coal particles of two sizes are pasted on the disc separately for investigation. The disc was placed on the sliding plate assembly. The specimen was fixed inside specimen holder. Load on the pin made of liner material is provided on the loading pan by putting different weights. The test specimen then gives stress on the coal particles which is pasted on the disc surface. The disc rotates clockwise direction. The rotation of the disc was set using controller of the pin-on-disc machine.

Fig. 2. Pin-on-disc wear measuring machine

5. The methodology

As the test specimen is in contact with the coal particles, the material loss of the test specimen takes place due to abrasion which is shown in Fig. 3a,b. In Fig. 3a, the image represents the test specimen on the disc surface making contact with the coal particles on the disc. Image representation of contact stress between the test specimen and coal particles with application of load is shown in Fig. 3b. For dry abrasion wear test, the coal particles were pasted on the disc is shown in Fig. 4a-c. To paste the coal on the disc surface, at first the disc surface was made coarser up to a thickness of 4 mm on 8 mm thickness of disc plate. On the coarser surface of disc adhesive was provided and molding was performed to fix the coal to its position on the disc. The disc pasted with coal particles was warmed up at 40°C to remove moisture contents from coal surface. The prepared disc was placed on pin-on-disc experimental set-up. On pin holder, attached with cantilever beam in pin-on-disc, the test specimen was fitted to make the contact of pin with the disc. The dry abrasion wear test was separately conducted on 500 µm and 710 µm particle size of coal by varying the load from 5 N to 35 N. Abrasion tests were carried at linear distance of 2500 m by taking care of changing rpm and making subsequent change in circumferential distance on the disc by applying load from 5 N to 35 N with an increasing step of 5N. From the dry abrasion test the results of weight loss was measured at electronic weight balancing machine. The weight loss was calculated before the dry abrasion test and after the dry abrasion test. The accuracy of the electronic weight balancing machine was ±0.001 mg.

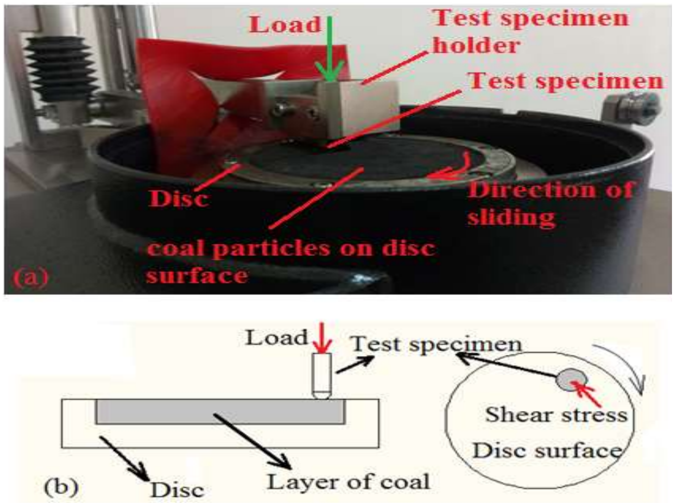

Fig. 3. (a) description of test specimen on the disc and direction of sliding, (b) distribution of shear stress on the disc surface

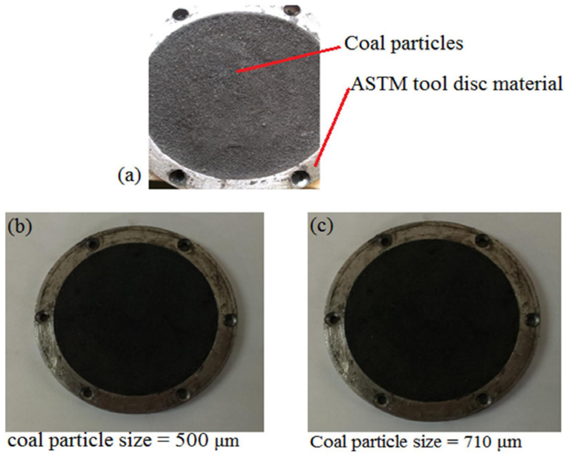

Fig. 4. (a) coal particles pasted on ASTM tool disc, (b) 500 µm coal size particle pasted on the disc, and (c) coal particle size of 710 µm pasted on the disc surface

6. Results and discussion

6.1. Experimental Investigations

Results of experiment performed on test specimen are plotted in Fig. 5a-d. Experiments were conducted at constant sliding distance of 2500 m. Weight losses of test specimen at sliding

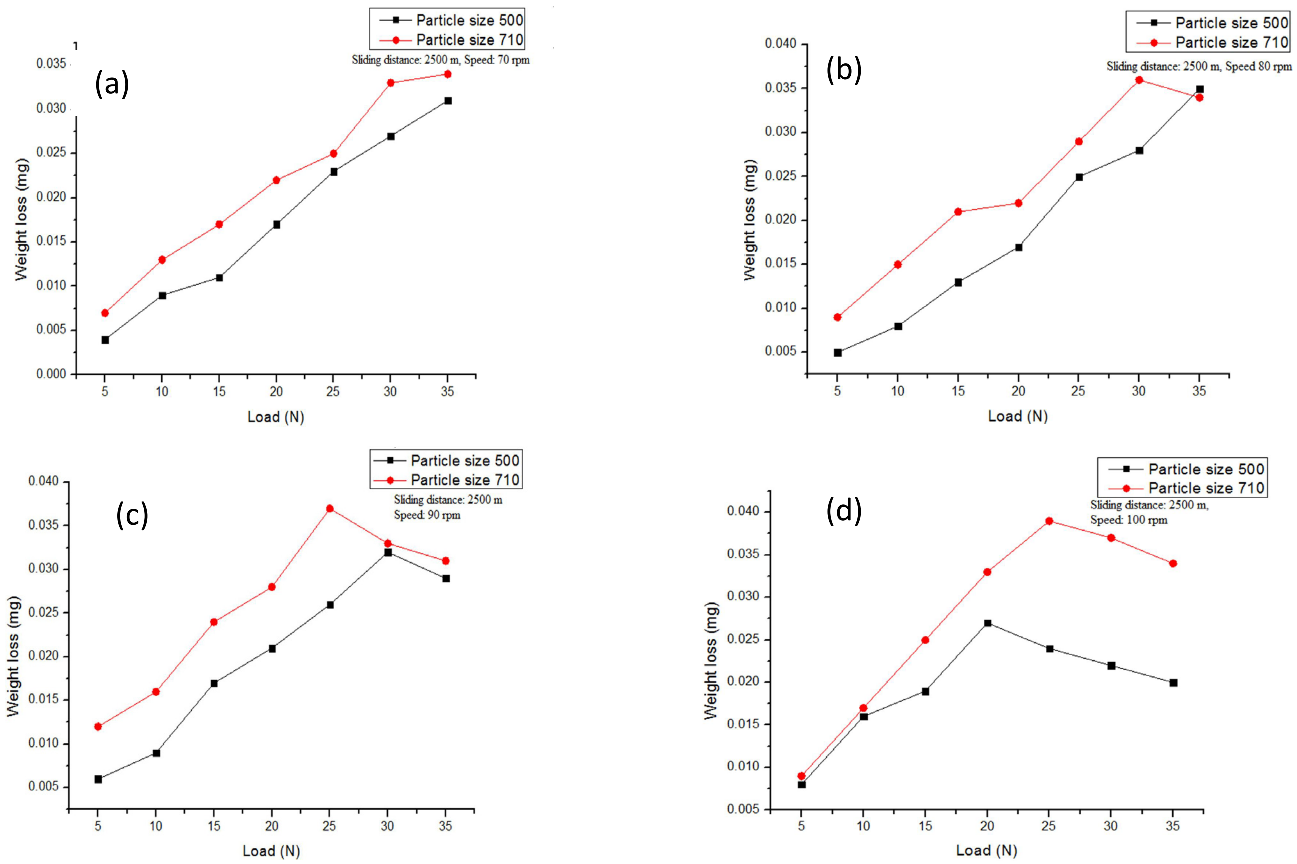

Fig. 5. Result of weight losses at constant sliding distance of 2500 m and: (a) at sliding speed of 70 rpm, (b) at sliding speed of 80 rpm, (c) at sliding speed of 90 rpm, and (d) sliding speed of 100 rpm

speed of 70 rpm are plotted in Fig. 5a. Results of weight losses have an increasing sequence with the application of load from 5 N to 35 N. Large particle size of 710 µm results more weight loss as compared to small size coal particle 500 µm. In Fig. 5b, results obtained at speed of 80 rpm are plotted. At higher load of 30 N, weight loss of test specimen at particle size 710 µm is 0.036 mg. But the weight loss obtained at 35 N is 0.004 mg. For abrasion test conducted on particle size of 500 µm, weight loss increases with an increase in load. Further with an increase in speed of 90 rpm the weight loss, as plotted in Fig. 5c, was obtained as 0.037 mg at 25 N load far test specimen at particle size 710 µm. Though at 30 N load on test specimen, weight loss decreased by 0.004 mg. It then decreases by 0.002 mg at load of 30 N. It was also noticed that at particle size of 500 µm the highest value of weight loss obtained as 0.032 mg at 30 N. Further at step increase in load of 5 N weight loss decreases by 0.003 mg. Results of weight losses at speed of 100 rpm are plotted in Fig. 5d. In Fig. 5d, as the load increases from 5 N up to 25 N weight loss increases for particle size of 710 µm. Thereby a decrease in weight loss has been noticed at 30 N and 35 N. Similar observations in decrease in weight loss were also noticed for particle size of 500 µm. But high value of weight loss was obtained at particle size of 710 µm.

From the observations of weight loss at higher load at particle size 500 µm and 710 µm, it was noticed that coarser the particle size more is the wear as observed at high load. This is due to work hardening property of Mn-steel made as test specimen for the experiments. The ability of work hardening of Mn-steel is to resist against wear. The property of work hardening is dependent on dipole interaction and stacking fault energy (SFE) [3]. Due to dipole interaction, there is an improvement in attraction field between carbon-manganese (C-Mn). Due to which there is increase in resistance against dislocations of C-Mn. Also, work hardening of Mn-steel material depends on the theory of SFE. It describes the formation of strain induced martensite in Mn-steel with the increase in load. Therefore, there is increase in strain hardenability of Mn-steel material [4]. Dini et al. [5] also reported the phenomena of phase change in Mn-steel at higher load in sliding abrasion. They reported that manganese-steel material has austenite phase. In sliding abrasion when load is increased on the Mn-steel material then austenite phase changes to strain induced martensite ($\gamma \rightarrow \varepsilon$ or $\acute{\alpha}$) phase. The strain induced martensite phase has enhanced strain hardenability which resists movement of C-Mn bonding [6]. The property of work hardening is also correlated with the development of new asperities in sliding abrasion. In sliding abrasion as the load increases on the test specimen the asperities gets de-fragmented from its parent region. This brings out new surface roughness on the test specimen with the increase in load. Therefore, generation of new surface layer results in change in surface microstructure from austenite to martensite phase as a result of work hardening property of Mn-steel material [7,8].

6.2. Design of Experiment

6.2.1. Identifying the important factors for analysis of weight loss

One of the favorable conditions to identify wear is by measuring the weight loss. To investigate the influence of operating conditions like load, sliding distance, speed and particle size on weight loss, design of experiment was performed. The current analysis of identifying the influence of operating conditions on weight loss is by adopting design of experiment (DOE). DOE quantify the relationship between the operating conditions which is the input factor for DOE. Quantification of result was analyzed by finding the limit for each factor which is between low and high value as presented in Tab. 1.

TABLE 1

Input factors and levels

Input Variables	Unit	Levels	
		Low (–)	High (+)
Load	N	5	35
Sliding distance	m	1000	2500
Speed	rpm	70	100
Particle size	µm	500	710

6.2.2. Conducting the experiments according to the DOE

Analysis of dominating factors like load, sliding distance, speed, particle size on weight loss was studied with DOE. DOE is a full factorial design where wear test was conducted from combination of input factors between low and high level as presented in Tab. 2. Based on the full factorial design, experiments were conducted on pin-on-disc wear abrasion test machine. From full factorial design weight loss was analyzed with ANOVA to investigate the dominating behavior of input factors namely: load, sliding distance, speed, and particle size. The ANOVA was performed at 95% confidence level. Below 5% level of confidence for an input factor, the p-value was selected as the significant contribution towards weight loss.

6.2.3. Result analysis using ANOVA

The ANOVA result is presented in Tab. 3. In the Tab. 3 of ANOVA, the p-value of load, sliding distance, interaction of load with sliding distance is less than 0.05. This is below 5% level of confidence with R-square value as 0.9886. It states that load, sliding distance and interaction of load with sliding distance is having significant contribution towards weight loss. Based on ANOVA Tab. 3, regression equation was developed which is presented in Eq. 1.

TABLE 2

Results of wear based on full factorial design

Run	Input Variables				Response
	Load (N)	Sliding distance (m)	Speed (rpm)	Particle size (µm)	Weight loss (mg)
1	5	1000	100	710	0.007
2	5	2500	70	500	0.017
3	35	1000	70	500	0.022
4	35	2500	100	710	0.031
5	35	1000	100	710	0.024
6	5	2500	100	710	0.018
7	35	2500	100	500	0.028
8	35	2500	70	500	0.027
9	35	2500	70	710	0.029
10	5	1000	70	710	0.003
11	5	2500	70	710	0.020
12	35	1000	70	710	0.026
13	5	2500	100	500	0.019
14	35	1000	100	500	0.021
15	5	1000	100	500	0.005
16	5	1000	70	500	0.004

TABLE 3

Results of ANOVA for weight loss

Source	p-value
Model	0.0003
Load (N)	<0.0001
Sliding distance (m)	<0.0001
Speed (rpm)	0.5003
Particle size (µm)	<0.0001
Load ×Sliding distance	0.0049
Load × Speed	0.5003
Load × particle size	0.0248
Sliding distance × Speed	0.8902
Sliding distance × particle size	0.8902
Speed × particle size	0.8902
R-Squared	0.9886
Adj R-Squared	0.9659

$$\begin{aligned} \text{Weight loss (mg)} &= 0.006684 + \\ &+ (0.0071984 \times 10^{-4} \times \text{load}) + \\ &+ (0.001913 \times 10^{-5} \times \text{sliding distance}) + \\ &+ (0.01833 \times 10^{-7} \times \text{load} \times \text{sliding distance}) + \\ &+ (3.57143 \times 10^{-7} \times \text{load} \times \text{particle size}) \end{aligned} \tag{1}$$

The validity of the regression equation was checked with number of wear test experiments. From wear experiments it was observed the accuracy of the regression equation is less than ±12% error of the result compared with the measured weight loss which is presented in Tab. 4.

6.3. The Worn Surface after Abrasion

The worn out surface of test specimen was analyzed using FESEM microphotographs. FESEM results for the wear experiments conducted on particle size of 500 µm are presented

TABLE 4

Confirmation of wear test results based on measured and predicted weight loss

Load (N)	Sliding distance (m)	Speed (rpm)	Particle size (μm)	Measured weight loss (mg)	Predicted weight loss (mg)	%Error
5	1000	70	500	0.007	0.00761	+8.01
10	1200	75	500	0.008	0.00852	+6.11
12	1500	85	500	0.009	0.00889	–1.23
17	2500	95	500	0.010	0.00985	–1.52
5	1000	70	710	0.008	0.00798	–0.25
10	1200	75	710	0.010	0.00927	–7.30
12	1500	85	710	0.011	0.00979	–12.3
17	2500	95	710	0.012	0.01132	–6.00

in Fig. 6a-c. Fig. 6a-c represents worn out surface of test specimen at load of 5 N, 25 N and 35 N respectively. FESEM microphotographs for the worn out test specimen at particle size of 710 μm are presented in Fig. 7a-c at load of 5 N, 25 N and 35 N respectively.

At load of 5 N for particle size 500 μm and 710 μm, the test specimens have scratches on the surface. The amount of scratch due to small sized particle is less as compared to the scratch due to large sized particle. With an increase in load on test specimen damages are more. At 25 N load on test specimen at particle size 500 μm the damages were observed more with more number of scratches. Whereas, at particle size of 710 μm the damages observed on the test specimen at 25 N load is groove formation with increase in number of scratch. Also, some amount of cracks on the surface was also observed. At higher load of 35 N on test specimen at particle size of 500 μm the damage was observed as formation of grooves with decrease in number of scratches. But for the particle size 710 μm and load of 35 N, groove length observed to be decreased with decrease in number of scratches. The change in wear types with the increase in load is due to change in surface microstructure, which is from austenitic phase to strain induced martensitic, of Mn-steel made test specimen and increase in work hardening property has been observed.

7. Conclusions

Weight loss of Mn-steel material was examined at particle size of 500 μm and 710 μm using pin on disk apparatus. Results of experiments were summarized as follows:

1) At speed of 70 rpm weight loss on test specimen increases with the increase in load. With the increase in speed of 80 rpm weight loss of test specimen at particle size 710 μm decreases at 35 N after attaining highest load at 30 N. But for the speed of 80 rpm weight loss increases with the load at particle size 500 μm. As the wear test performed at 90 rpm then weight loss at particle size increases up to 25 N and at higher load above weight loss observed to be decreasing. Whereas, weight loss decreased at 35 N at particle size 500 μm. Further increase in speed of 100 rpm, at particle size 710 μm weight loss after increase up to

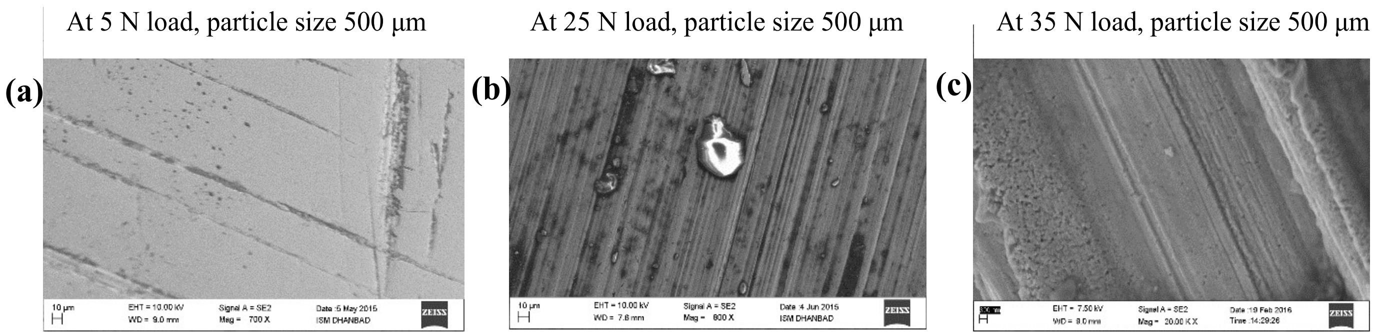

Fig. 6. Microphotographs of worn out test specimen at particle size of 500 μm (a) at load of 5 N, (b) at load of 25 N, and (c) at load of 35 N

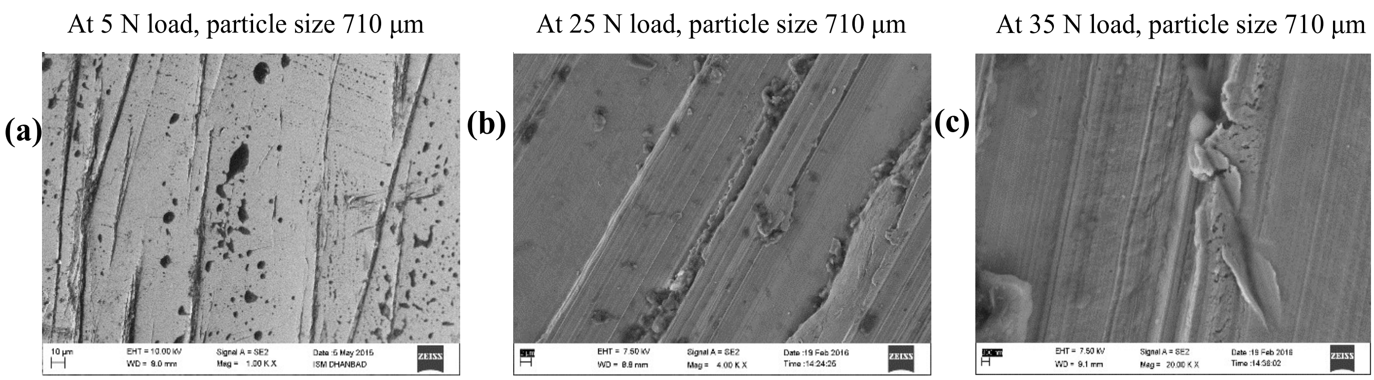

Fig. 7. Microphotographs of worn out test specimen at 710 μm particle size for: (a) the test conducted at 5 N load, (b) 25 N load, and (c) 35 N load

25 N it decreases at 30 N and 35. At particle size 500 µm, weight loss decreases after 20 N. From the results of experiment for weight loss it has been observed that coarser the particle size more would be the wear of material. But for work hardening material, weight loss decreases with the increase in load. In the present study Mn-steel material was selected to perform wear test. As the Mn-steel is having work hardening property therefore there is decrease in weight loss was observed.

2) Work hardening of Mn-steel results in transition in wear mechanism from scratch to groove formation.
3) Experiments performed using DOE shows that the factors like load, sliding distance, interaction of load with sliding distance and interaction of load with particle size is having p-value less than 0.05 (Tab. 3). So, these factors have significant effect on weight loss.

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