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Elucidation on Abrasive Wear of Cast Iron and Alumina plus Calcia Stabilized Zirconia Composite Coatings

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Abstract— In the present investigation, an attempt has been made to develop a composite coating system that may be considered as a substitute for conventional cast iron liner used in internal combustion engines. The atmospheric plasma spray coating technique was used to achieve coatings. Specific wear rate and a wear mechanism of Cast Iron and composite coatings ($ZrO_2 \cdot 5CaO + Al_2O_3$) applied on CI of coating thickness 250 µm were discussed. In pursuit of this, an abrasive tribological test has been carried out as per ASTM G132 standard. The tests were conducted on commercial available Alcon abrasive medium and at different loading conditions viz. 5 N, 10 N, &15 N and at different sliding speed. Results found that the 250µm coating system is more desirable coating system compared to CI coating system since the specific wear rate continuously decreased with the increase of sliding speed and normal load and may be good for tribological applications. The detailed comparative study has been presented in this experimental work.

Index Terms—Plasma coatings, $ZrO_2 \cdot 5CaO + Al_2O_3$, abrasive wear, specific wear rate.

1 Introduction

The metallic cylinder liner has to work under variable load and often undergoes local plastic deformation due to the presence of hard particles formed by internal or external means [1]. The primary cause of an abrasive wear is due to unburnt carbon particles and soot's that often leads to surface fracture. It has been also found that material transfer takes place between piston and cylinder liner at their weakest point and eventually results in rapture. The mechanism of wear in cylinder liner has been mainly classified into two categories: (1) Physical mechanism and (2) corrosion mechanism. The physical mechanism includes adhesion, scuffing and abrasion, often dependent on the relative hardness and surface finish of the mating materials [2]. Scuffing happens in the absence or inadequate lubricant between the mating surfaces. The inner surface of cylinder liner often undergoes work hardening resulting material hardening. The hard surface is often spalling off considered as abrasive debris and often found increased wear rate [3]. In-cylinder liner abrasive wear often understood by series of vertical grooves resulted due to plowing of soft phase by the harder phase [4]. Chemical wear often characterized by the presence of metallic oxide, sulfides, organic salts etc. which are sometimes harder than the metallic surface and are formed during combustion process in the presence of oxygen, humidity and temperature [5].Y.J. He et al. proposed that extraordinary performance characteristics of a ceramics can be achieved by altering the material composition [6]. It has been found that the grain size is an important factor in characterizing the wear behavior of ceramic materials [7]. It has been also reported that when 20 wt. % alumina added in a zirconia matrix its hardness and toughness increased compared to zirconia ceramic and also good for tribological applications. It has been also reported that composite ceramics exhibit better performance than single phase T-TZP [8]. Earlier investigations have indicated that fine-grained ceramics have lower wear rates in comparison with that of coarse-grained ceramics in both sliding [9].Y.Wang [10] has investigated the abrasive wear characteristics of plasma sprayed nanostructured alumina-titania coatings (250 to 600µm) on a mild steel substrate. He has reported that the worn surfaces of conventional coatings exhibit grooves, plastic deformation, and microfracture features. However, the dominating mechanism of material removal of nanostructured coatings is due to grain dislodgement as found by Xu and Jahanmir [11].In other investigations, it has been reported that the composition viz.ZrO_2 + 8%Y_2O_3, ZrO_2 + 20% Y_2O_3, and $Al_2O_3 + ZrO_2$ coatings have superior and extended wear life against cast-iron [12].In general, it is understood that the wear resistance of the material is closely related to its microhardness, toughness, coating defects and the ratio of its hardness to the hardness of the abrasive [13,14]. Recent development includes the use of SiC as a slurry after honing resulting in local hard points and improves wear resistance properties[15].

Different material combination exhibits diverse wear mechanism and wear rate and no single scientific model available that can be used as the basis for a wear study. Above research gap open avenues for further improvement in the area of composite coatings. For this purpose, a preliminary investigation first carried out on test specimens before coatings applied directly to the engine cylinder. Composite coatings $ZrO_2 \cdot 5CaO + Al_2O_3$ in 50:50 proportions applied to CI substrate using APS technique and specific wear rate is determined for the CI substrates and coated specimens 150µm and 250µm. The test was conducted under different loading conditions 5, 10 & 15N at 150, 200 & 250 sliding speed. An effort has been made to find the suitable coating system that may enhance the wear life of the coating system.

2 Experimental Details

2.1 Selection of materials

Cast Iron plates of size 15×15 mm were trimmed from the 10×10 cm plate and glued with cylindrical pins shown in Fig.1. Six specimens were prepared for the abrasive wear test purpose. Three specimens were prepared for CI and three specimens for 250µm coating systems. The schematic of sample plates and specimens are shown in the Fig.1

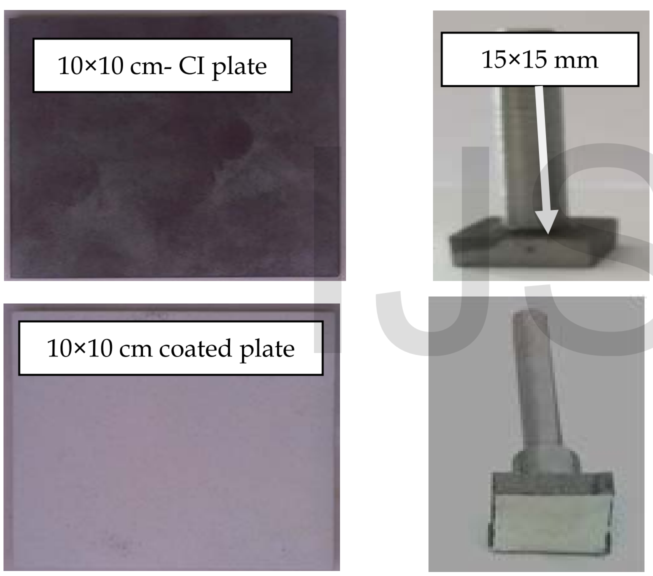

Fig.1 Schematic of CI plates and coated specimens

2.2 Atmospheric plasma spray coatings

The atmospheric plasma spray (APS) coating technique was adopted to coat the specimens. The parameters followed during the APS coating process is given in Table 1. The schematic of the coating system is shown in Fig.2

TABLE 1 –Plasma spray parameters for different coating materials

Materials/Powders	Primary gas (Argon) Pressure (Bar)	Secondary gas (Hydrogen) Pressure (Bar)	Carrier gas Argon flow (lpm)	Current (amps)	Voltage (volts)	Spray distance (mm)
Top coat $ZrO_2.5CaO+Al_2O_3$	3.7	3.45	35	500	65	65-76
Bond coat Fe38Ni10Al	6.9	3.30	35	500	65	50-76

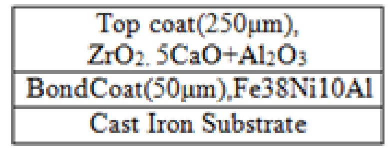

Fig.2. Schematic of coating systems

2.3 Abrasive wear test setup

An abrasive wear study was carried out on Ducom-pin-on-disk Tribometer. The schematic of Tribometer is shown in the Fig.3.The parameters used in the abrasive wear study is shown in Table 2.

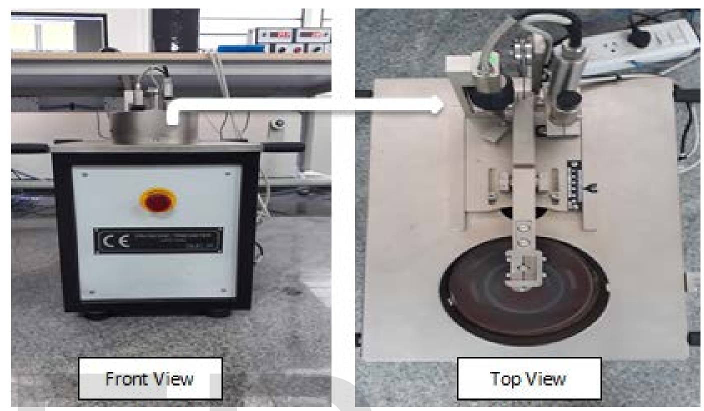

Fig.3. The schematic of Ducom- digital Tribometer

TABLE 2 -Plasma spray parameters for different coating materials

Rpm	150,200 & 250
Track diameter	60 mm
Load	5,10 & 15 N
Sample size (mm)	10 mm×10 mm
Abrasive disk	Alcon (grit size 120µm)
Test temperature	Room temperature
Rubbing duration	900 sec

2.4 Abrasive wear test procedure

Initially the track diameter of 60 mm was set. The cylindrical part of the specimen was fixed in a special fixture connected to the lever arm. The specimen was aligned perpendicular to the Alcon abrasive disk (grit size 120µm) ensuring no transverse movement of the specimen. With the help of digital transducers, the time and rotational speed of the disk was adjusted. A load of 5 N was applied to the hanger thus producing a normal load on the surface of the specimen. The digital Tribometer vortified with software connected with the computer automatically records the data points of wear and friction during the rubbing time. The same procedure repeated for the remaining specimens. The wear studies were carried out at a speed of 150, 250, and 250 rpm and at a load of 5, 10, & 15 N normal loads individually on CI specimens followed on the coated 250µm coated specimens.

2.5 Wear rate calculation

Wear rate was calculated based on cumulative volume loss per unit sliding distance. The formula used to calculate specific wear rate is shown in equation 1.2,3 & 4. The volume loss/height loss data obtained from the data set points from the software.

Wear rate = volume loss/sliding distance, (mm^3/m) …… (1)
Sliding distance= sliding velocity× Time, (m)……………… (2)
Specific wear rate = Wear rate/Load, (mm^3/mN)…………… (3)
Sliding velocity = (2×π×N×d/2)/60, in (m/s) ……………... (4)
Where: N is rpm, d track diameter, (m)

2.6 Characterization

Post abrasive was characterization was done on abraded CI and on abraded coated ($ZrO_2.5CaO+Al_2O_3$) specimens using an optical microscope and SEM technology respectively. An attempt has been made to explain the wear mechanism with the help of wear versus time graphs and micro images results. The wear mechanism of CI and 250 µm coated specimens were discussed in detail in the result and discussion section.

2.7 Microhardness test

Vicker microhardness test was carried out using Clemex CMT.HD model. An average of three trials has been presented. The parameters used to determine microhardness of CI coated specimens are shown in Table.3.

TABLE 3. Vickers microhardness test parameters

Load	100 g.
Dwell time	10 sec.
Indenter	Diamond pyramid (120°)

3 RESULTS AND DISCUSSIONS

3.1 Discussion on wear

The graph of wear versus time clearly shows that when sliding speed increase from 150 rpm to 250 rpm the wear also increases with time. However, the sudden rise in wear found is different at different sliding speed reason attributed to, at the higher sliding speed the asperities of the substrate (CI) make a faster contact with the hard abrasive asperities thus faster removal of soft material takes place At 5 N normal load and 250 rpm the maximum wear is found to be approximately 325µm. Whereas at 200 and 150 rpm the approximate wear found to be 150 and 60µm respectively under abrasive conditions. Similar results obtained at 250 rpm 10 and 15 N normal loads where the wear is found to be approximately 450µm and 750 µm respectively. In all the cases similar trend is observed as the load and sliding speed increases the wear also increases. The mechanism of abrasive wear of a metallic substrate over hard abrasive may be explained with the help of Fig.4 (5 N,10 N,& 15 N) and Fig.5 (a), (b), & (c).

It is observed that all the specimens under 5, 10 and 15 N loads irrespective of sliding speed; demonstrate of two phases in wear variation. The first phase comprises a very short period of an increase in wear related to a running-in-step. Second stage shows wear almost remains constant during running in period. In the first stage, the wear suddenly increases with time which is due to shear stresses developed between the hard asperities of the two surfaces in contact. Wear debris is generated after initial running-in-stage. Thus, the process of wear renders to the three body abrasion situation rather than two bodies sliding with the release of wear debris. The formation of debris confirmed from the optical images obtained after post wear refer Fig.5.

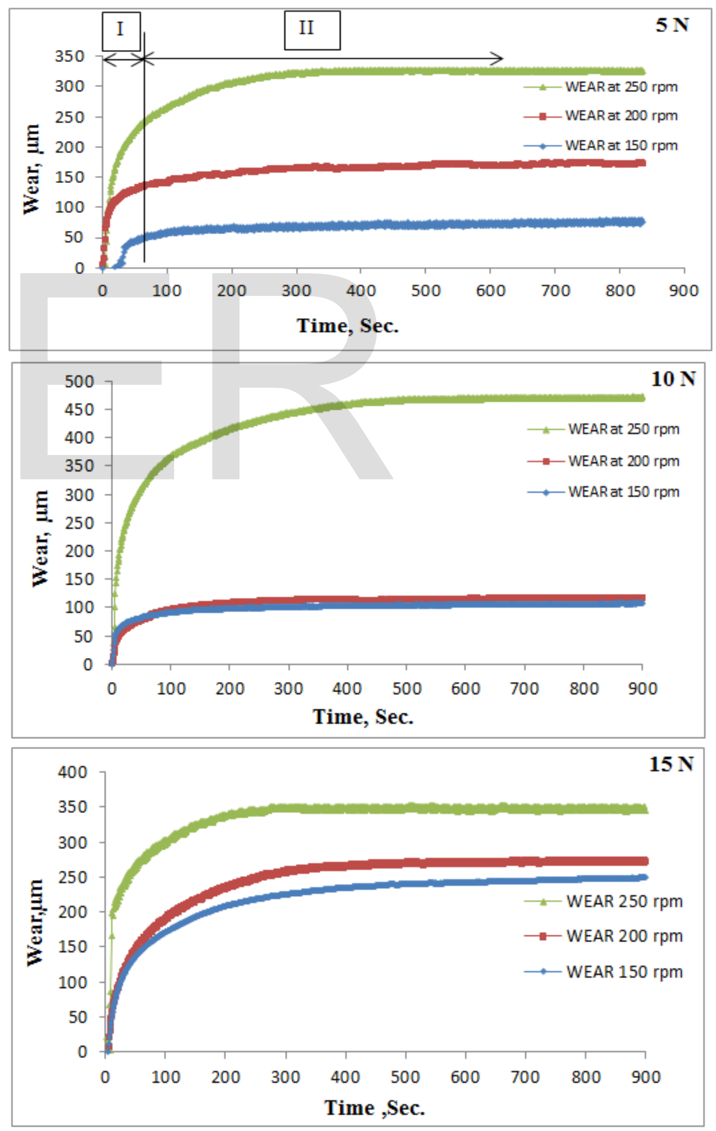

Fig.4 Wear versus Time graph of CI specimens at 5 N,10 N and 15 N

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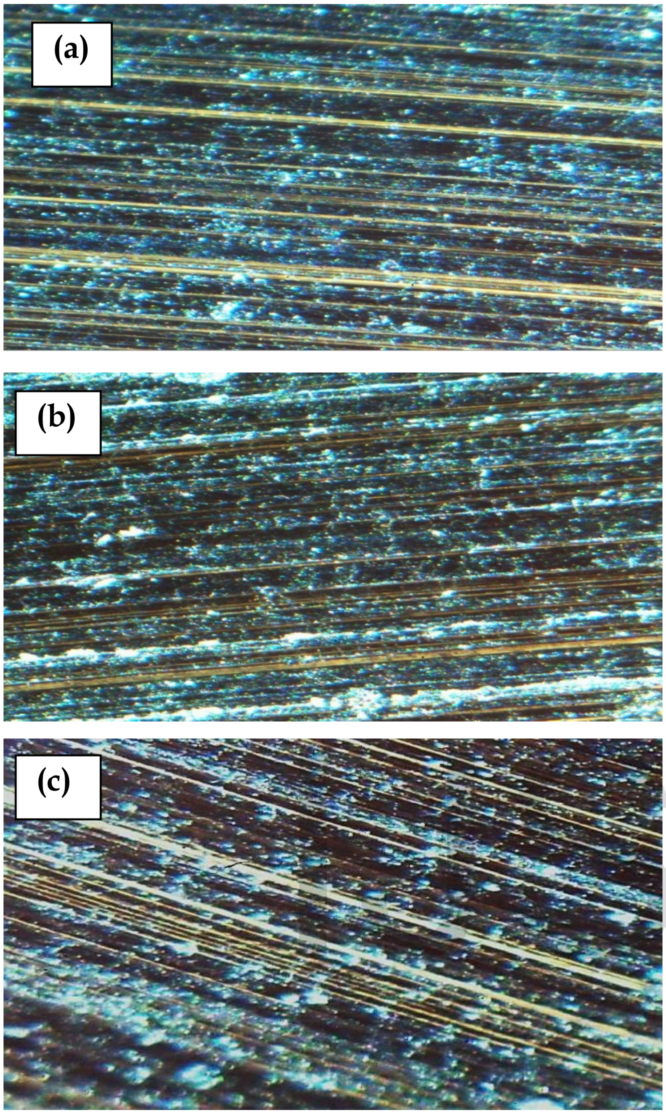
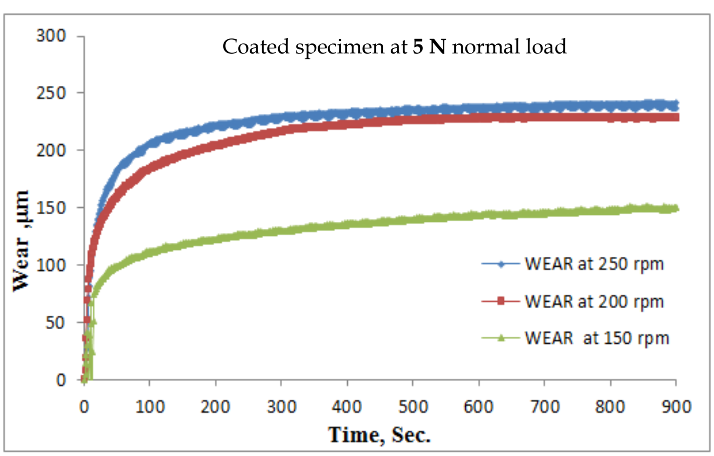
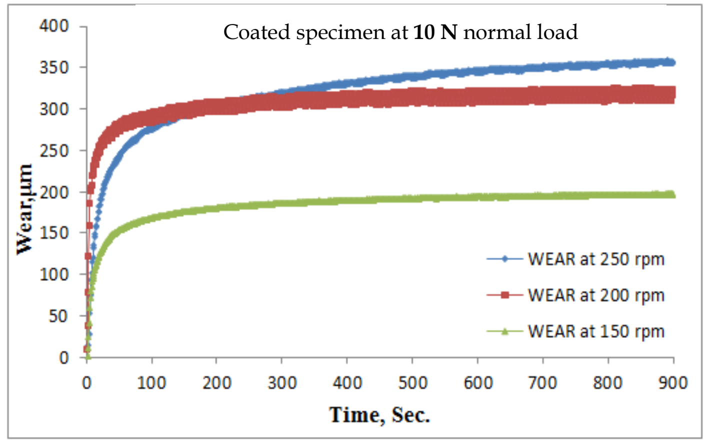


Fig.5 Optical microscope wear images of CI specimens at (a) 5 N (b) 10 N ,& (c) 15 N





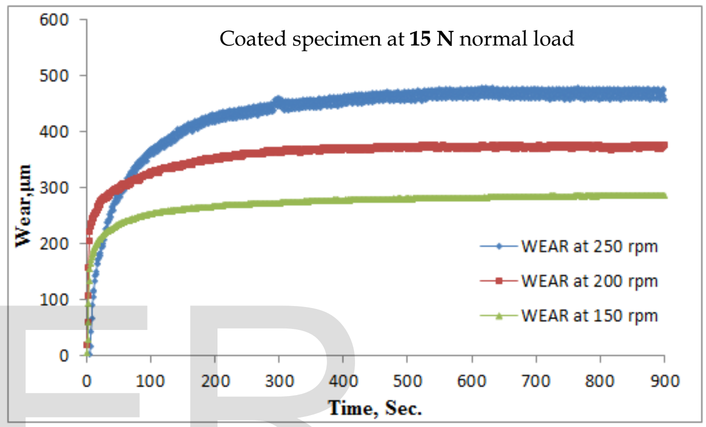


Fig.6 Wear versus Time graph of 150 µm coated specimens at 5 N, 10 N &15 N normal load

From the Fig.6 at 5 N normal load, it is evident that the wear of 150µm coating system at 250 rpm at 5N reported less with an approximate wear value of 245 µm compared to CI, 325 µm, refer Fig 5 and Fig. 6. Also, the similar trend observed at 10 N.However, at the higher load the coating demonstrated little higher wear reason attributed to, at higher load and sliding speed 250 rpm the asperities of the coated surface makes a larger contact area with the abrasive disk and subjected to more wear. In both the cases, CI and 150µm coated specimens the wear versus time graph exhibit asymptotic function value/wear rate. The wear versus time graph in case of the coated system suggested that the wear rate of the coating started early and remains constant during the sliding period compared to CI specimens. This phenomenon is observed more or less same irrespective of applied load and sliding speed.

At 150 rpm the specific wear rate of cast iron specimen found to decrease from 5 N to 10 N. However, the specific wear rate in case of 250µm coating system found gradually decreasing. A similar trend is observed at 200 and 250 rpm refer to Fig. 7.The reason for gradual decrease in specific wear rate attributed to change in the characteristics of the coating (morphology).Also in other ways, it can be understood as follows: As the abrasive disk grows older the asperities of the abrasive disk couldn't able make complete contact with the coatings even when the load is increased from 5 N to 15 N. Thus the waer decreases even after increase in load irrespective of sliding speed. Other reason attributed to the presence of soft phase of c oatings continuously sliding over the hard asperities of the abrasive disk.

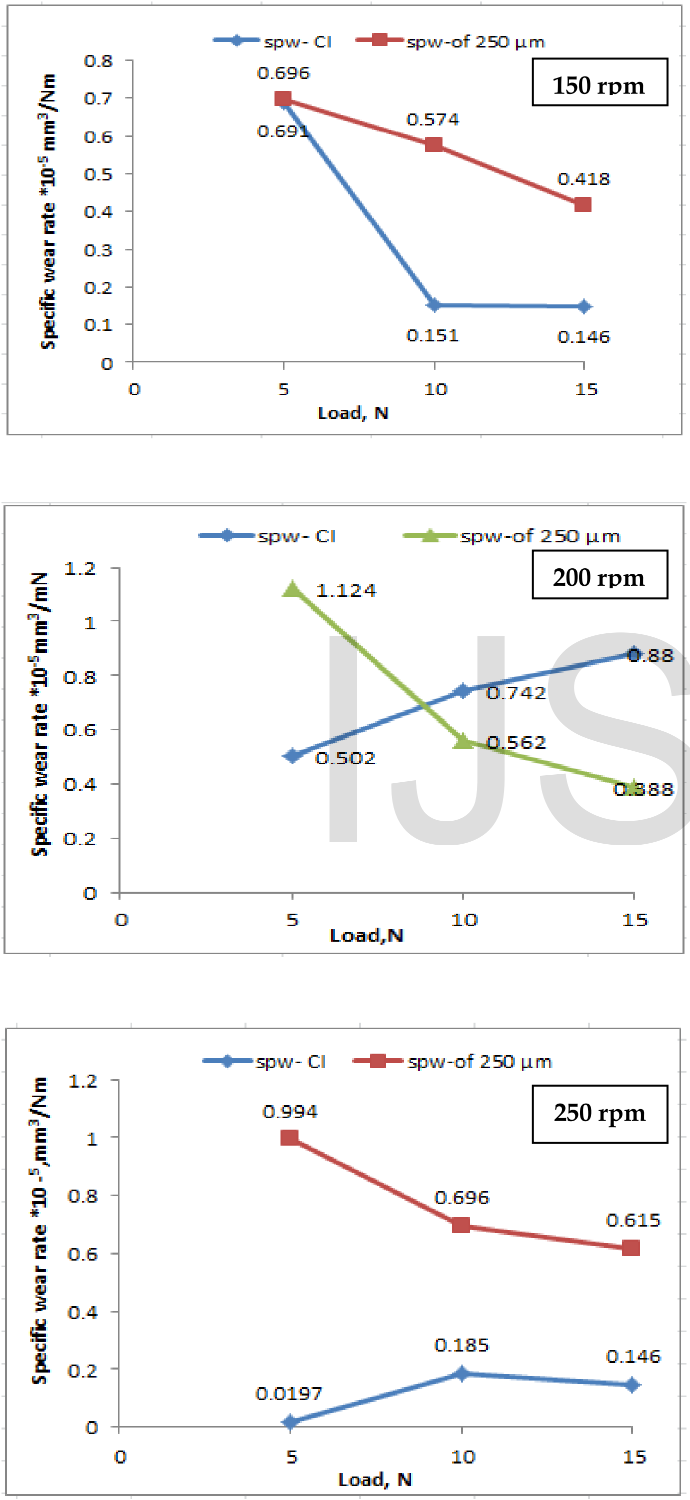


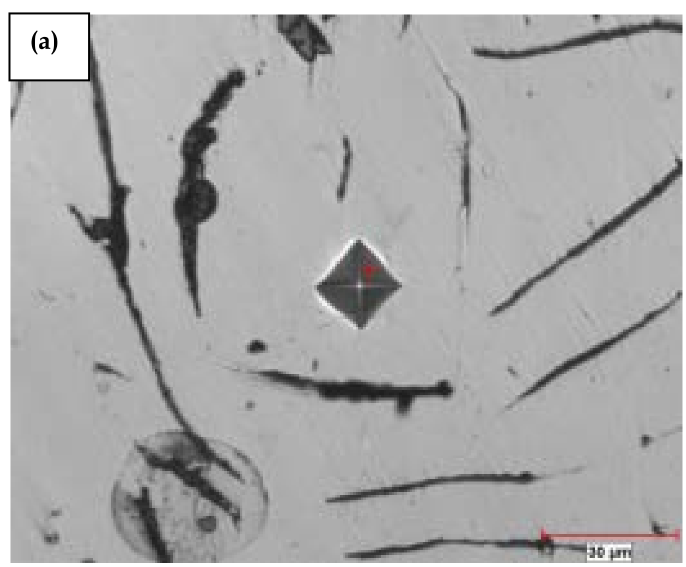
Fig.7. Specific wear rate versus load at 150, 200, & 250 rpm.

3.2 Wear mechanism

Cylinder liner subjected to high mechanical stresses, heat, and corrosion. It is essential to control all these parameters for extended life. This can be possible by improving the surface topography, microstructures, material hardness and roughness of the materials. Roughness plays a crucial role in altering the wear process. At 0.8µm Ra the maximum wear of 4.5 microns has been reported under abrasive condition [15]. The average roughness of the CI specimens found to be----. It is evident from Fig. 5 (a),(b), & (c) the severity of damage is quite high observed as wear scars of narrow and deep grooves marked on the surface. Torn surfaces can be also seen at all the sliding speed irrespective of applied loads 5, 10, 15 N. In order to prevent continuous smearing of the surface, the inner surface of the cylinder liner is provided with plateaux separated by the cross-hatched pattern of grooves [16]. To overcome such exaggerate stress mark silicon carbide are embedded on the surface after honing thus improving the wear resistance of the surface[17]. Due to the presence of debris between rings and plateaux often give rise to high contact loading resulting high wear rate. In the present work the wt. % of C & Si found to be 3.854 and 1.91 respectively and the remaining alloying constituents are shown in Table 3.The wt. % of other alloying elements viz. titanium, phosphorus and molybdenum along with casting technique can influence the hardness of the material and occasionally found a decrease in wear rate [5, 15]. The average microhardness of the CI substrate and for 250 µm coating system found to be 395.07HV0.1. The micro-indentation micrograph for CI and 250 µm coated specimens shown in Fig.8 (a) and (b) respectively.

TABLE 4.Constituents of Cast Iron

Element	C	Si	Mn	Cr	Cu	P	S	Ni
Weight %	3.854	1.91	0.04	0.03	0.02	0.082	0.097	<0.05



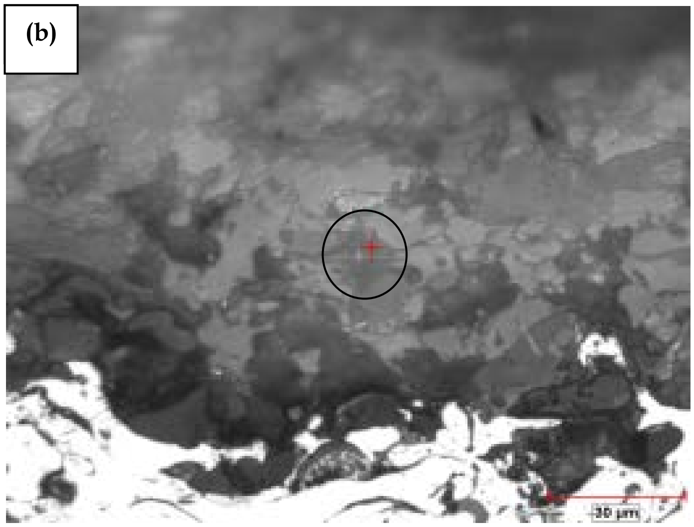
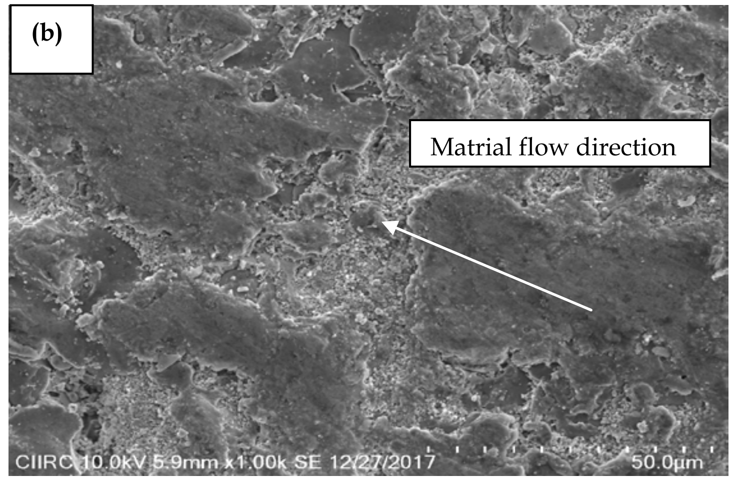


Fig.8. Micrograph of shows micro-indentation mark (a) CI (b) 250µm coate system

In case of a 250µm coated system, the topcoat consists of alumina and calcia stabilized zirconia, the wear mechanism of the coatings is explained as follows. The wear has taken place mainly by localized abrasion and is enhanced by the exfoliation of the splats. During the exfoliation mechanism, due to high friction initiation of crack takes place between the two splats or adjoining splats of the same lamella. During cyclic loading of the surface, the crack is propagating along the splat boundary, leading to its final exfoliation from the worn surface. It has been found that the weak interfaces among the lamellae at the top coat failed to result in gradual delamination of the top coat also delamination found extended from top to bond coat interface from the axis of normal load. This degradation mechanism is found to induce the localized wear of the coating, however, sliding effect shadows the effect of abrasion at the higher loads. Fig. 9 shows the abraded surface micrograph of 250µm coated specimens.



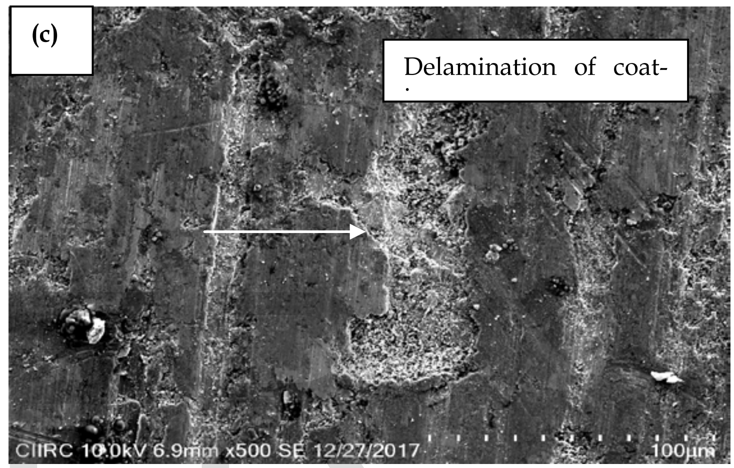


Fig.9. Micrograph of 250µm coated specimens after abrasive Wear at (a) 150 rpm (b) 200 rpm (c) 250 rpm.

4 CONCLUSION

From the above experimental studies it can be concluded that at the higher load, above 10 N normal loads the composite coatings demonstrated continuous decrease in wear rate irrespective of sliding speed but in case of cast iron at higher load constant wear may be anticipated.

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