# WEAR CHARACTERISTICS DURING COATING OF YSZ+$Al_2O_3$ ON CAST IRON SUBSTRATE

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***In recent years, the coating of different materials inside the cylinder liner has emerged as a prime focus of research among the scientists as it improves the efficiency of the engine. In this paper, the coating material, YSZ +$Al_2O_3$ with equal proportion were coated on the cast iron substrate using two bonding materials (Iron Nickel Aluminium composite powder (Metco 452) and Nickel Aluminium cermet (Metco 410 NS)) with the three-coating thickness of 100µm, 200µm and 300µm. Initially, the wear characteristics were carried out and properties like the coefficient of friction (CoF), wear rate for different load conditions were determined. The analyses of the worn sample were studied in details with the aid of SEM images. Further, the scratch studies for the worn samples were also carried out.***

***Keywords:*** *plasma spraying, wear, microhardness, coating thickness, the coefficient of friction*

## 1. Introduction

During the working on I.C engines, the piston slides inside the cylinder liner and generates friction during its rapid movement. In this process, the piston generates more heat and is then transferred to the liner where it easily gets eroded. There are a lot of studies in improving the function of the liner, through the selection of materials, surface hardening, plating, liner coating and other ways. From all these studies, it is understood that the cylinder liner should have high wear resistance and thermal resistivity for its better performance. Recently, there are studies in the improvement of the wear resistance by applying thermal barrier coating inside the cylinder surface. But, several factors influence the coating material that bond with the substrate. The intensity of spraying on the coating material and the grain size formation decides its wear characteristics. P.Ctibor [1] discussed the importance of spraying parameters and mentioned that the improper spraying parameters will lead to the formation of porous inside the coating. V Boneche [2] discussed the effect of intensity of plasma spraying on particle size inside coating during wear studies and observed that the debris that is generated creates cracks inside the coating and affect the sliding properties. Further, there are also studies in comparing the wear properties during the lubricating and non-lubricating condition. Kristina [3] studied the tribological behaviour of ceramic coating inside the stainless steel tube and found that Alumina-Zirconia composition (15+85%wt) has better wear properties than un-lubricated conditions. Further, she carried out structural and tribological characteristics of zirconia and alumina-based ceramic coating and observed a drastic improvement in the wear properties by the addition of coating inside the cylinder liner during underwater lubricating condition [4]. There are also studies in understanding the liner with the different coating materials and the wear properties. Rajaratnam [5] observed the better microstructure and abrasive wear properties of AISI1040 steel surface with Cr2O3 ceramic materials. In some cases, the microcracking was increased due to the increase in microhardness on the coating surface. N Krishnamurthy [6] mentioned that the microstructure, roughness, porosity and coating thickness of the coating material depends on the wear properties. He noted that the wear properties also depend on the abrasion and when the bond comes in contact with the disc, the bond loses its adhesion. D M Kennedy [7] examined the wear resistance for coated and uncoated materials and further erosion, impact and dynamic wear studies were carried out. He discussed the methods of finding wear through simple experimental procedures. E M Leivo [8] came out with some interesting experiments, where he sealed aluminium phosphates over chromium oxide coating. He mentioned that the hardness value increased from 200 to 300HV units. The abrasion and wear resistance were also increased with this method. S Dallaire [9] also carried out similar work, where he discussed the sealing properties for high temperature and the friction, wear loss and ceramic piece damage for the coating. C S Ramesh [10] studied the spray coating techniques and studied the corrosion and erosion properties of the coating material and mentioned that Inconel-718 has good wear properties and erosion. The slurry wear rate of Al6061 was decreased to Inconel 718 as substrate. Jianguo Zhu [11] studied the plasma coated thermal

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barrier coating at an elevated heat-treated temperature of 1400°C and the hardness value was decreased with an increase in porosity. Shunyan Tao [12] studied the wear characteristics of Nanostructures YSZ coating and measured the Microhardness by Vickers indentation test and observed the increase in hardness and wear resistance values for the coating material. Meysam [13] mentioned that the ZrO2–Y2O3 nanostructure, when elevated at 1050°C and then deposited on a substrate will produce the high value of hardness (21.7 GPa). Further, the temperature increased with the increase in the hardness value. Apart from wear studies, there were also studies on the mechanical strength of the coating materials. Shiladitya Paul [14] studied the effectiveness of Plasma-Sprayed Thermal Barrier Coatings and the stiffness of plasma-sprayed zirconia topcoats is much lower than that of dense zirconia. Song [15] carried out the various mechanical strength test and found the optimum hardness value of 300±50 HV due to the inclusion of Al2O3 when compared with FeAl coating of hardness 185±35 HV.

Overall, there are a lot of studies and observations by the various researchers in understanding the wear characteristics of different alloys and coating materials. It should also be noted that the lower coating thickness may easily peel off from the substrate due to the rubbing of the coating attached to the bond material. The increased coating thickness may also lead to poor wear performance due to poor adhesion between the coating layers. There need some studies in understanding the wear characteristics by varying the coating thickness for better adhesion. To study in detail, the three coating thickness is selected for our analysis by coating the equal proportion of YSZ+$Al_2O_3$ (50:50) on the cast iron substrate. The specimens are then fixed to pin on disc machine and 5N, 10N, 15N loads are applied by taking different samples. The COF and wear characteristics are discussed initially. The coating is applied through Atmospheric plasma sprayed thermal barrier method, which is commonly used in coating cylinder liner [16, 17]. The coating thus produced should have high resistance to wear and corrosion. Such a coating should possess the ability to withstand at high temperature [18]. In this work, to check the resistance of coating towards wear, coated samples were subjected to abrasive wear test in which a pin on disc tribometer was used. Many parameters such as load, track diameter, sliding distance and speed of the abrasive disc are considered for the investigation. The effect of the coefficient of friction on the characteristics of abrasive wear was studied. Apart from the above, any other wear parameter will influence the stability of the coatings were studied. The SEM images of worn samples are studied to understand wear behaviour during the process. Finally, the strength of the coating is analysed by studying microhardness on the substrate and are discussed in detail.

## 2. Experimental Details

The substrate is made up of cast iron having 12mm diameter and grit blasted to get a coarse surface for proper adherence of the coating. The three different types of coating, the topcoat with a mixture of 50% $Al_2O_3$ +50% $8Y_2O_3ZrO_2$(Metco 204NS-Yttria-stabilized zirconia), first bond coat with Iron Nickel Aluminium composite powder (Metco 452) and second bond coat with (Metco 410NS-$Al_2O_3$30(Ni20Al)) Aluminum Oxide-Nickel Aluminium cermet were selected for the process. The three coating thickness, 100,200 and 300 microns with a bond coat thickness of 75 µm were prepared. For hardness value on the coating, Leica Vickers Microhardness analyzer (MMTX7, make: MATSUZAWA, Auto) was used and the experiments are carried out as per ASTM E384 [19]. The abrasive wear test is done as per ASTM G99 [20] standards using tribometer. Portable digital surface roughness measurement (Mitutoyo) Tally surf is used for surface roughness measurement. In all the specimens, each bond coat is having the thickness is equal to 75µm and topcoat thickness varies from 100 µm, 200 µm and 300 µm (Termed as C1, C2 and C3).

## 3. Result and Discussion

### *3.1 Coefficient of Friction and Wear Rates*

During the spraying process, for 100µm thickness, some of the particles did not melt properly which leads in improper adhesion even when there is an impingement of successive layers. This results in the poor thermal conduction between the layers that leads to improper bonding between them and also with the substrate. This results in the microcracks due to the difference in thermal cyclic effects. During the wear study, the higher wear and higher coefficient of friction are recorded during the testing process. The microcracks may lead to a detachment from the subsequent layers due to poor bonding and higher wear rate are recorded during the process. With the increase in the coating thickness to 200 µm the bombardment of large spraying particles aids in increasing the bonding between the coating and substrate. The bonding strength also improves due to improvement in thermal cyclic effect which reduces porosity and increase the bonding strength between the layers of coating materials. The small cracks found help in reducing the wear rate and friction. With the increase in the coating thickness to 300µm, even last particle may help in improving bonding strength but increase in the subsequent layer of coating materials results in a large accumulation of thermal cyclic effect which may results in residual stresses after solidification. Even this residual stress may found for lower coating thickness, the lower thermal cyclic effect did not create residual stress or small

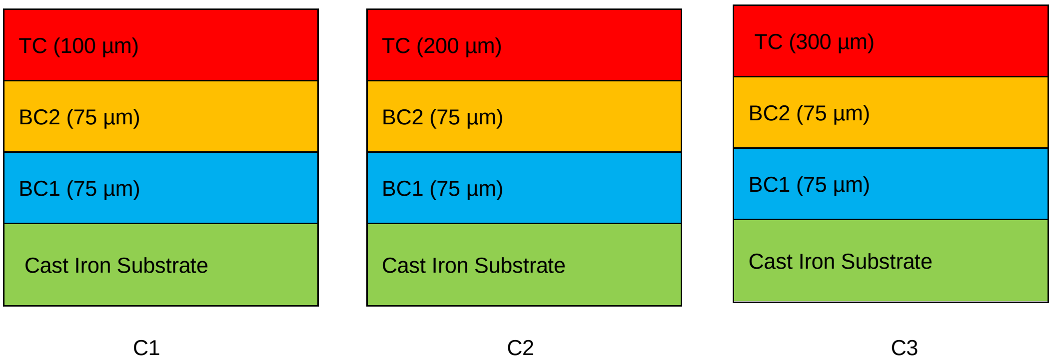



Fig.1 - The architecture of Thermal Barrier Coating on Cast Iron Substrate.

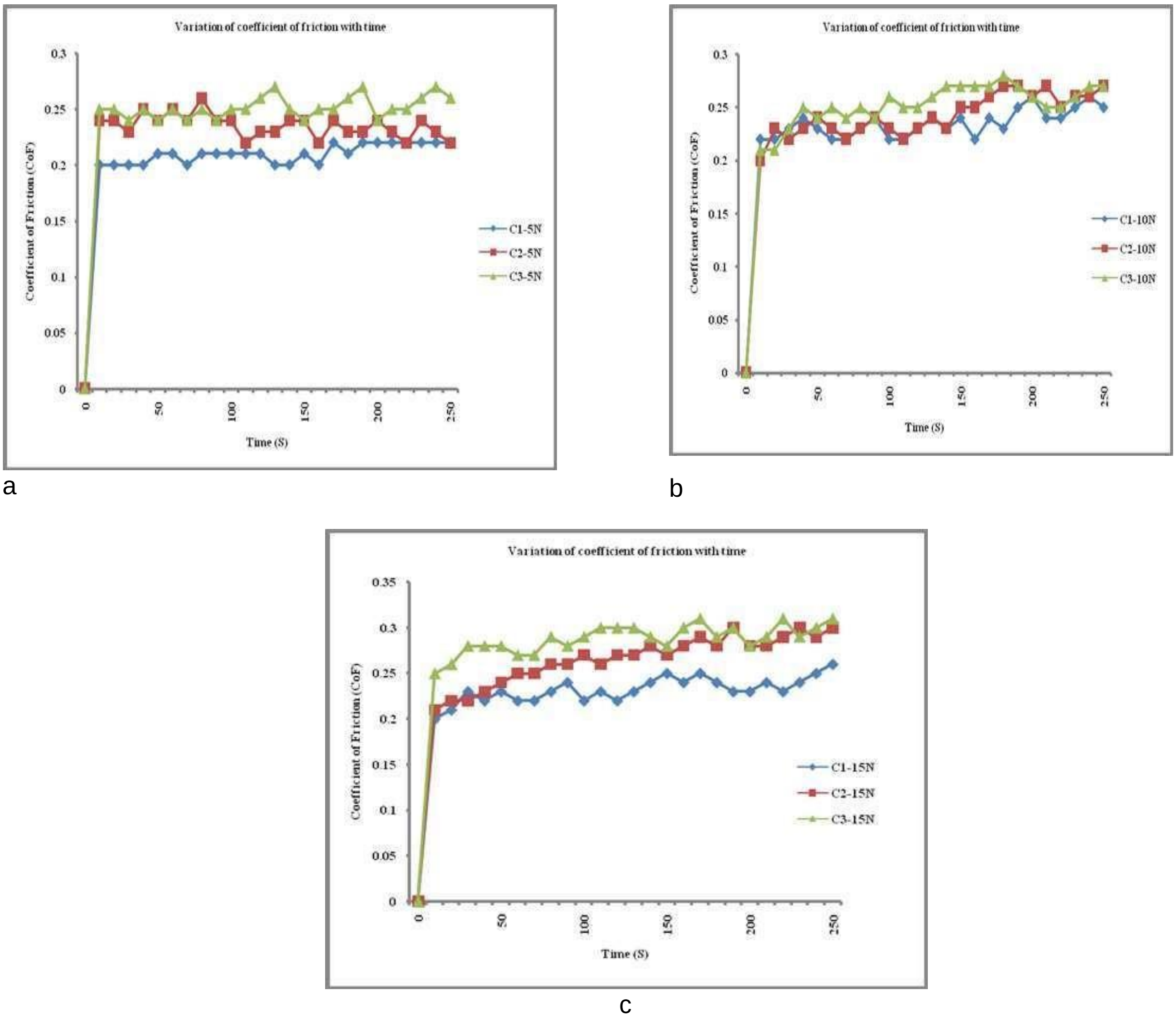



Fig: 2 - Coefficient of Friction v/s Time graphs for Coatings on cast iron substrate at (a) 5 N (b) 10 N (c) 15 N load.

value of residual stress may form. At higher coating thickness the change in the solidification rate between the molten particles increases the wear rate and friction.

The Coefficient of friction (COF) versus time graphs is shown in Figure 2. From the graphs, it is observed that in all coating systems, there is a sudden rise in friction coefficient for a short period. After this, the COF slowly increases. In some of the coatings, the COF remains constant from initial rise to the end of the test. The sudden increase in COF at the initial stage is mainly due to the abrading of asperities with the disc. These undulations, after detachment trapped between specimen and disc producing three-body abrasions which in turn increase the COF. The debris formed during this period is frequently brushed out and now the flat surface of the coating is exposed to the rotating disc. During the wear of this surface, a very small quantity of debris is formed and brushed out frequently. Due to this, there is a gradual increase in COF in some of the coating systems and remains constant in other coatings. The COF mainly depends on the contact area between specimen and disc. If the contact area is more, the COF will be more. For all the coating systems (C1, C2, C3), the coefficient of friction increases with the load applied. The contact area between specimen and disc and contact stress increases with the load which are the main reasons for increasing the COF. In general, the COF of abrasive wear is mainly affected by the load or contact stresses which are easily measurable. The effect of this typical load or the contact stress is critical since it increments the zone of contact and profundity underneath the surface at which the most extreme shear stress happens and also results in the plastic deformation of particles. Figure 3 shows the variation of COF of different coating systems with the load. From this, it is observed that COF of C1 coating decreases with the load while the COF of C2 and C3 increases with load. COF increases with the increase of topcoat thickness for all coating systems. This is mainly due to the increase in average roughness of the topcoat with its thickness [21]. For C1, C2 and C3 coatings, the average roughness is about 7.8185, 8.044 and 8.2707µm. From the COF graphs (Figure 2 and 3), it is noticed that the COF has increased concerning the topcoat thickness and indirectly explains the effect of roughness on surface roughness.

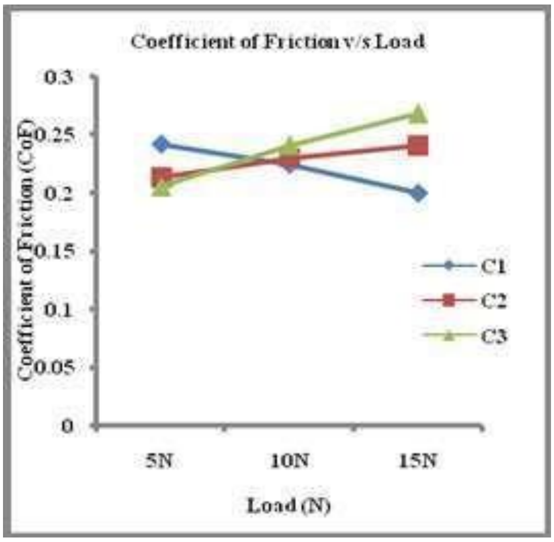
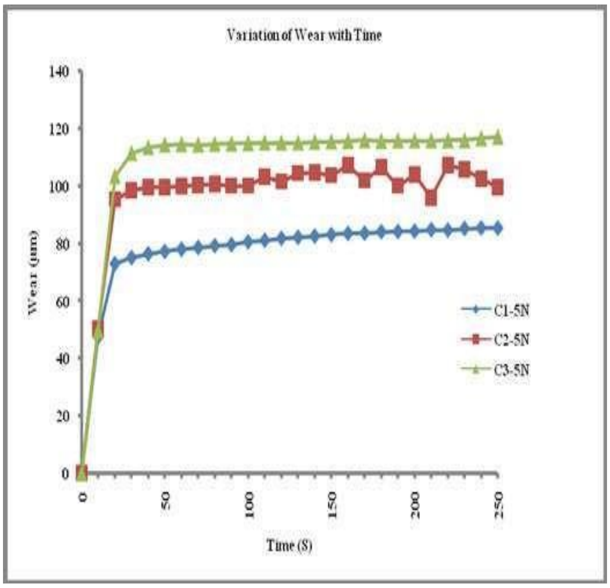



Fig: 3 - Coefficient of friction v/s load graphs for different coating systems.

### 3.2 Wear of Coating Systems

The wear versus time graphs for all coating systems is shown in Figure 4. These graphs consist of two distinct regions. The first region indicates an as sudden rise in wear for a short period and the second region shows a gradual increase in wear for some of the coatings and remain constant for

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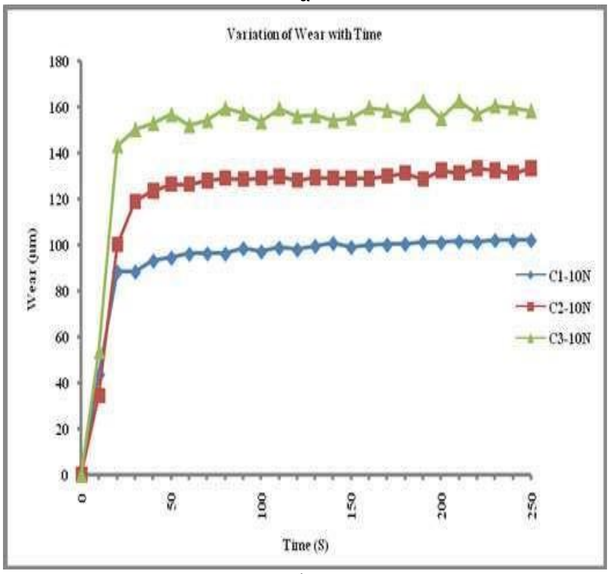


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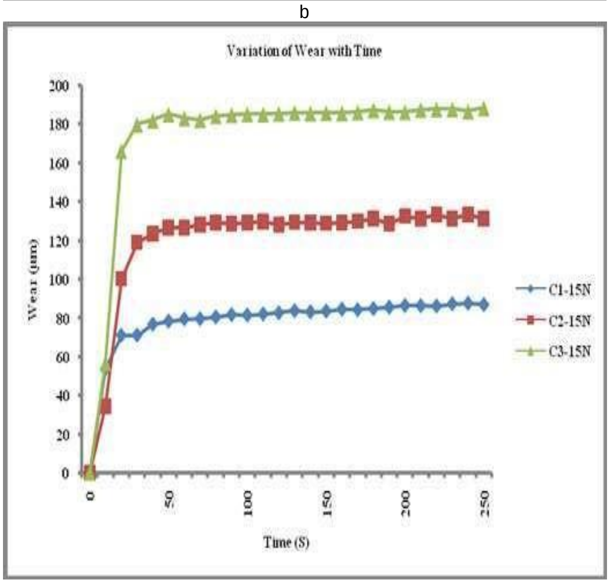



c

Fig. 4 - Wear v/s Time graphs for Coatings on cast iron substrate at (a) 5 N (b) 10 N (c) 15 N loads.

others. The main reason for the sudden rise in wear is the initial roughness of coatings. Whenever specimen comes in contact with the disc, the asperities or undulations of the coated surface undergo wear. Since the contact area of these undulations is very small, in a short period, they will be detached from the specimen surface showing a rapid rise in wear.

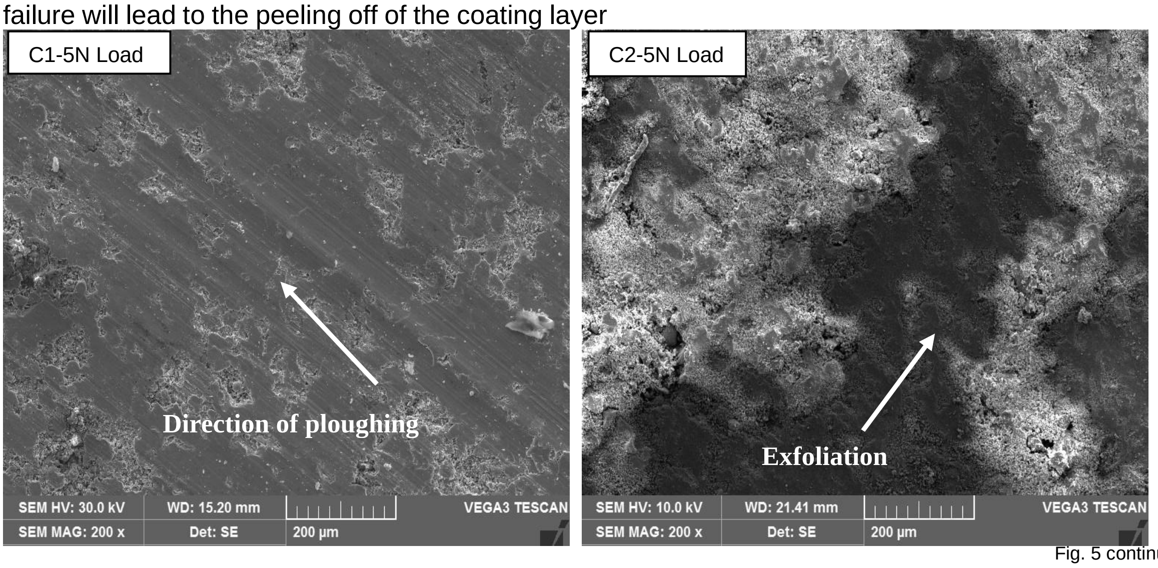
The second stage of wear versus time graphs of C1, C2 and C3 coatings (Figure 3) show slight or no variation of wear with time. This is mainly due to the high bond strength of these coatings. During the second stage of wear, the increase in the temperature at the mating surface lodges out uneven particles producing glazed or smooth surfaces and these surfaces offer less friction which results in small or no wear in the second stage.

### *3.3 Wear Mechanism of coating systems*

The wear test specimens are subjected to microscopic observation by the help of SEM. From SEM images (Figure 5), it is understood that the wear of the ceramic topcoat is mainly because of the ploughing mechanism. In this mechanism, a lip is generated due to friction between the coated specimen and abrasive wheel which is identified in the C1 sample under 10N load. It initiates a crack between two splats of the same lamella as ploughing action continues. These crack will propagate towards the splat boundary due to cyclic loading and ultimately will exfoliate from the worn surface. Also, there will be a generation of stress field due to sliding action which also propagates further the cracks which will be perpendicular to the junction between coating and substrate interface and towards the thickness of the coating. This method of wear mechanism is called an exfoliation mechanism [22]. In case of atmospheric plasma spraying of yttria-stabilized zirconia and pure alumina coatings, the presence of the weak interface between the successful lamellae of the coating layer appears to have been failed. This failure will lead to the peeling off of the coating layer by layer due to the axial loading during the wear mechanism. This mechanism will result in rapid wear of the ceramic coating and hence play an important role to increase the wear.

Wear behaviour and its mechanism in the bond coat are very similar to that of topcoat wear. Researchers have observed that initially, the wear will take place between the coated specimen and the abrasive wheel like two-body abrasion. After sometimes, some wear debris will stick to the coated specimen and adheres on its surface in the form of a tribofilm. This tribofilm consists of plastically deformed wear debris, as well as a plastically deformed coating material and chemically altered coating surface [23]. In case of the absence of tribofilm formation, the coating would not oppose the continuous removal of the materials from the coating surface from the harder counterpart abrasive disc.

In general, it is understood that the resistance to wear of the coating systems firmly depends on its microhardness, sturdiness, defects in the coating and the proportion of coating hardness to the abrasive wheel hardness [24-27]. The charts of specific wear rate versus microhardness as shown in Figure 6 demonstrate that the specific wear rate increments with the diminishing in microhardness of the coating. Thus the wear rate is higher for the coating with low hardness and the other way around [28]. The high hardness is attractive for acquiring the enhanced wear resistance, for both brittle and ductile materials [29-31]. The hardness significantly affects the wear of systems by components of plastic deformation where fracture sturdiness is a prevailing variable amid the procedure of wear including brittle fracture [31]. The coatings which utilise plasma spraying technique to deposit the material will have better connections between the hardness of the worn material and the different modes of wear in which plastic deformation is a noteworthy mechanism.

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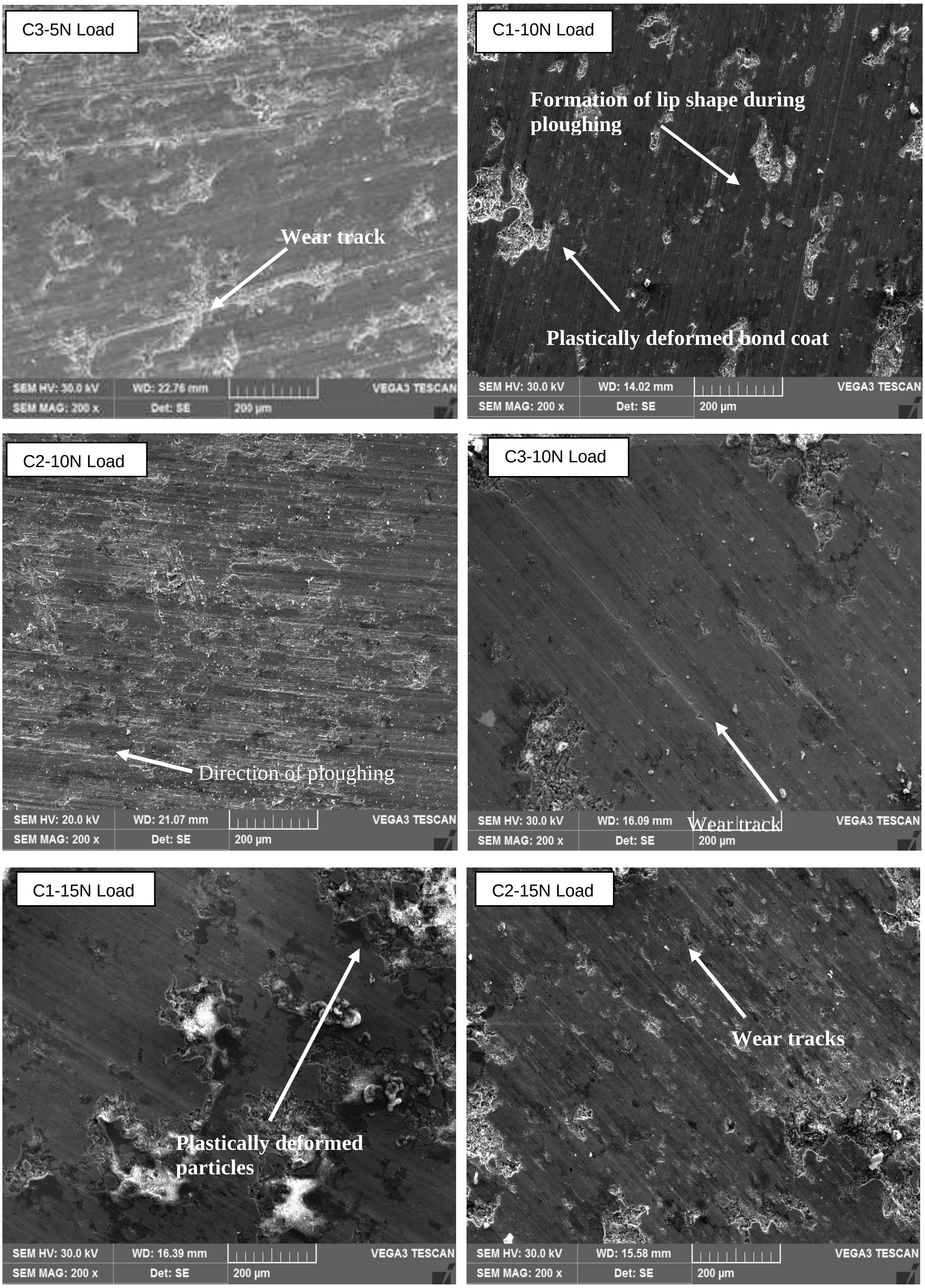


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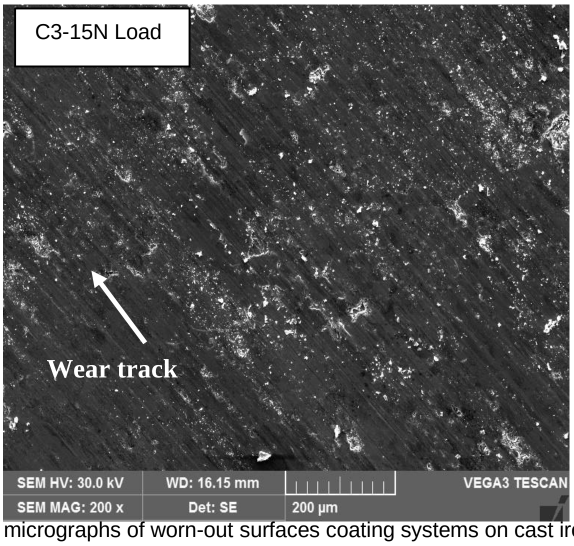


Fig. 5 - SEM micrographs of worn-out surfaces coating systems on cast iron substrate.

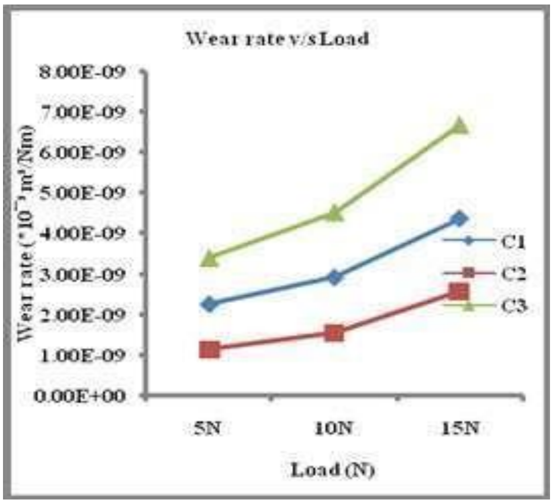


Fig. 6 - Wear rate v/s load graphs for different coating systems

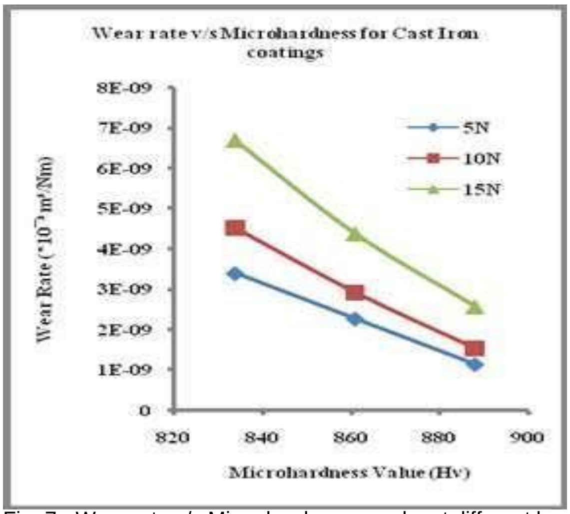


Fig. 7 - Wear rate v/s Micro hardness graphs at different loads

In general, the wear rate is calculated based on volume lose per unit applied load per unit sliding distance. The deviation of specific wear rate versus load is indicated in Figure 6. From the graph, it is noticed that the specific wear rate increases as the applied load increases. From the observations, it is suggested that the indentation depth not varies linearly with the applied load. For the higher coating thickness, the topcoat of the sample gets expelled with rapidly and makes the bond coat to come in contact with the rotating abrasive disc. At higher loads, the work hardening influences the abrasive wear and changes it into adhesive wear. Also, the friction coefficient is observed to be marginally lower at loads of 10, 15N compared to 5N load. At the point, the smaller applied loads tend to rebounce the contact area between the coated sample and abrasive disk along the sliding surface making the typical load vary. It is also evaluated that the factors, for example, adhesion, work hardening and densification separated from the abrasive procedure impact the friction behaviour in the steady-state zone.

Here, it is investigated that the specific wear rate of the coating decreases with the increase in microhardness of the top coat which is shown in Figure 7. The wear rate of coating systems also depends on the microstructure of coating systems. The microstructure of plasma sprayed coatings relies upon the lamellar bonding, including the horizontal crack density and shape factor and level of smoothing of the splats. It creates the impression that these microstructural highlights which are interesting to plasma-sprayed coatings may have a more noteworthy effect on their wear conduct than on their hardness.

In this work, there may be chances of development of tribofilm at the interface of rotating abrasive disk and bond coat due to trapping of wear debris. It is further necessary to wipe out the wear debris from the surface of the abrasive disc from time to time with the help of brush during the wear test. The above action will eliminate the development of tribofilm which in turn raises the wear at this stage. To know this, the SEM morphology of worn-out surfaces of coatings under 10N and 15N loads showed that the bond coat grains have deformed plastically, which gives the evidence for the wear that has happened due to adhesion also. It is also seen that the adhesion wear occurs when the substrate comes in contact with the abrasive disk. From the SEM micrographs Fig.7, it is familiar that the wear track width is increased with the increase in the applied load for coating systems. This increase in load will attribute to the increase in the surface contact area of the coated sample with the abrasive disc. The SEM images of worn-out surfaces clearly show the plough marks on the wear tracks. SEM images also show bond particles of plastically deformed which are generated due to squeezing of grains at the interface of the harder rotating disk and soft bond coating under the higher applied load where the indent is deeper into the coating and increases the depth of ploughing marks. The mechanism behind the ploughing is further explained as follows. When the wear test begins, there is a sudden rise in COF because of the underlying harshness from both the contacting components. This three-body abrasion is the basic reason for a rapid rise in the coefficient of friction during the running-in period. The increase in the coefficient of friction amid running-in-period is also reported by the earlier researcher [23]. The increase in COF may be due to the expulsion of hard particles from the similarly soft framework of the coating. Amid this period, there will be an increment in tangential force because of ploughing activity, which aids in the increase in the coefficient of friction (rubbing). In the second stage, one can see a reduction in coefficient of friction because of smoothening of hard particles present in the topcoat which were not expelled in the course of the primary stage. This process will produce the glazed surface in the coating. From this progression onwards, the rubbing coefficient which is pretty much the same until the point when the topcoat is expelled. In the third stage, it is foreseen that the bond coat of the specimen interacts with an abrasive disc. Since the bond coat material is delicately contrasted with topcoat, the material will be expelled quickly from the specimen, which will increase the coefficient of rubbing (friction).

### *3.4 Effect of Microhardness on Wear*

The micro-hardness for the different coating thickness is shown in Table 1.

The un-melted particles bombarding the substrate and its poor bonding results in decreasing the solidification rate for 100µm coating thickness. The formation of an increase in the grain size due to the poor solidification rate between the coating particles, which results in a decrease in its hardness value. There should be a wide dispersion of particles on the surface with improved heat transfer and solidification rate. This happens when the coating thickness is changed to 200µm. Here the porosity reduces during the process and which in turn increase the hardness value of coating. There is a proper adhesion between the coating material and disc which resulted in the reduced wear characteristics and improve coating properties. With the further increase in the coating thickness, the poor dispersion of particles and the possible formation of residual stresses between the layers results in the decrease in hardness value.

From the surface roughness measurement, there is an increase in the roughness value with the increase in the coating thickness. For lower coating thickness, un-melted particles or semi-melted particles when hits the substrate results in the poor bonding strength. During the wear test, the coating materials easily peel out from the substrate or levels smoothly and form a finer surface finish. An improvement in the bonding strength of the coating materials for its increase in thickness results in the formation of rough surface on the coating. With further increase in the coating thickness (300µm), the ploughing action of the coating particles makes more roughness and as a result, higher roughness values are recorded during its testing.

The wear analyses for the samples are studied through the SEM images and are shown in Figure 5. The coating material when applied in layers, results in the formation of residual stress between them due to its temperature difference. The residual stress initiates the crack and leads to a higher coefficient of friction and wear rate [6]. For the loading condition of 15N, the particles have ground into its finer shape. This results in plastically deformation of coating on the worn samples and results in finer surface roughness. The plastically deformed particles are also seen for higher coating thickness with the increase in wear tracks. For optimum coating thickness of 200µm, the plastic deformation of the coating material is not much seen from the images.

**Table 1**

Micro-hardness values for different specimens before wear test and after wear test.

| Test load: 100gm | | | |
|---|---|---|---|
| Dwell time: 10 sec | | | |
| Before wear test | | | |
| SAMPLE | C1 | C2 | C3 |
| Top Coat (YSZ+$Al_2O_3$) | 888 | 834 | 887 |
| Middle Coat (Metco 410NS) | 745 | 735 | 690 |
| Bottom Coat (Metco 452) | 193 | 224 | 211 |
| After Wear Test | | | |
| Hardness value on wear surface | 659 | 712 | 650 |

**Table 2**

Surface roughness values after abrasive wear

| | Ra | Rq | Rz |
|---|---|---|---|
| C1-15N | 3.008 | 3.881 | 17.493 |
| C2-15N | 3.289 | 4.122 | 20.054 |
| C3-15N | 4.308 | 4.482 | 22.738 |

The wear studies for three loading conditions (5N, 10N, 15N) are shown in Figure 6 and 7. In the case of lower coating thickness, the wear takes place through abrasion and a higher coefficient of friction is noted. Wear tracks increases with load [32] and also observed from our experiments, which indicates an increase in the mating surface that results in the reduction of abrasion. As observations made by several researchers, plough marks were also observed during this process and was much deeper for a higher load. The diffused particles of the coating materials may plot between the mating surface at this higher load and increase in deeper ploughing. With the change in the coating thickness, the weaker bonding between the coating materials leads to a lower coefficient of friction which increases thereby with the increase in pressure load. From the wear track, observe indicates the track in proper line which understands the wear that has happened due to ploughing with the larger coating the formation of residual stress helps in easy ploughing of the coating material where diffused coating material on the coating surface in the plastic form are observed. Even for lower coating thickness, the plastic deformation of the bond coat is also seen. It is understood that the formation of microstructure has a profound influence on the wear property due to the change in thermal cyclic affect the coarse grain formation will result in poor wear characteristics.

### *3.5 Overall Discussion*

The formation of study composition and its stability is vital during the coating process. This slurry is made to hit on the substrate depends on the velocity of slurry travel and its viscosity. Assuming the viscosity of the slurry during its movement and its velocity is constant, there exhibits complexity of slurry movement due to its rheological behaviour during the lower thickness, the lower viscosity of slurry may result in strong adhesion with the substrate, with the increase in the layer thickness, the viscosity increases due to the influence of rheology that present in the slurry due to its composition [33].

Increase in layer thickness results in the formation of cracks between the layers, this formation of cracks results in poor adhesion between layers. With the thinner thickness, the formation of cracks even though is less but its adhesion of on substrate may become poor results in poor wear characteristics as in case of 100 µm coating thickness. Here the bonding strength of the slurry, the cast iron substrate is due to its poor heat conduction resulting in easily peel off layers during its wear tests due to this lower hardness value is recorded for this process. The initial movement of the impingement of slurry on the substrate also results in shear stress due to the disorientation of the slurry for the substrate with continuous deposition of layers the force field on the metal solid-phase decreases resulting in small residual stress [34]. With the increase in coating thickness to 300 µm, there is an increase in the shear stress due to its slippage resulting in a poor bond between the layers. In this dynamic loading condition, a drastic increase in the thermal cyclic effect results in easy wear during its characteristics. In the case of 200 µm thickness, there is an improvement in the shear stress due to deposition of slurry with its materials in the previous layer. The bonding strength improves in this case where an improvement in the wear characteristics is observed due to its rigid bonding.

Overall, the motion of slurry is complex which finds difficult to adhere with the cast iron substrate initially and due to poor conduction of heat of cast iron, there is poor heat conduction from the slurry to cast iron which weakens the bonding between the layers. With the increase in coating thickness to 200 µm due to thermal balancing between the layers and slurry to the substrate takes place with increased shear strength. Further, an increase in coating thickness results in again poor slippage and reduce shear strength which further affects the wear characteristics of the coating.

## 4. Conclusions

The cast iron substrate was coated with the equal proportions of YSZ and $Al_2O_3$ materials for the three coating thickness (100,200 and 300µm) with atmospheric plasma spraying technique. The detailed wear characteristics for the three specimens were studied in details. During the wear studies, the thrust forces formed by rubbing the materials were absorbed by the substrate thereby increase its bonding strength at lower coating thickness. Also, the thrust force was repelled by the coating material, with the increase in the coating thickness and the bond strength reduced gradually during the process. The wear resistance is large for the lower loading condition and coat thickness. With the increase in the coating thickness, the wear increases with the increasing load condition due to the increase in the formation of the residual stress. The residual stresses may form due to the difference in temperature between the coating layers and poor conduction between the layers.

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