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Effects of Titanium (Ti) Addition on Wear Behaviour of Powder Metallurgy (P/M) Plain Carbon Steel

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ABSTRACT: Wear is a damage to solid surface that generally involves progressive loss of material and is due to relative motion between that surfaces. The present work aims to study the effects of Titanium (Ti) addition on wear behaviour of Powder Metallurgy (P/M) plain carbon steel. Elemental powders of atomized iron (Fe), graphite (C), and titanium were weighed accurately and homogeneously mixed to compose an alloy powders of Fe-1%C, Fe-1%C-1%Ti, then compacted into cylindrical billets of size (Ø25X33mm) using suitable circular die-punch set in a 100T capacity hydraulic press. The compacted specimens were subjected to sintering and subsequently sintered specimens were once again heated to a temperature 1000°C and hot upsetting was carried out on the heated specimens. Then the machining was performed on hot upset specimens to get wear test specimens of sizeφ6X50mm. Using design of expert (DOE) software, the sliding wear experiments were planned on pin-on-disc Tribometer. The images of maximum worn out surfaces and microstructures of the alloy steels were captured and compared with wear behaviour of the alloy steels. The results are represented on 3D &2D Surface plot for comparing the response factors of both the alloy steels. It is found that the delamination wear is predominant at higher loads on both the alloy steels. The empirical equations for mass loss and coefficient of friction with respect to load and speed are developed for both the alloy steels.

KEYWORDS: Wear; Mass loss; P/M alloy steels; Co-efficient of friction.

1 INTRODUCTION

Powder metallurgy (P/M) is a field of science which concerns with the processing of metal and ceramic powders to form of desired shape. Powder characterization and homogenization is the process which is responsible for the continuity of properties in all region of the metals. In the compaction process, high pressure is applied to give powders to the desired shape. The compacts are sintered at the temperature below the melting point of the chemical element, which increases its strength and the secondary operations are used to attain the required properties. Automobile and industrial parts and machinery parts are also produced on P/M technique. In present work, the tribological study was carried out on plain carbon steel and the addition of Ti to the plain steel was also studied in order to find the influence of Ti on wear behaviour of the plain carbon steel. The wear tests were conducted using pin-on-disc tribometer adopting ASTM standard.

A number of researchers has carried out research work in the field of wear on P/M materials. Dhanasekaran et al. [i] have studied the wear behaviour of molybdenum di sulphide added Fe-C-Cu steels and have reported that the addition of molybdenum disulphite increases the compressibility and increases the part density and increases the strength and hardness better than the base composition. Increasing the percentage addition of MoS_2 is found to improving the wear resistance of the alloy steel. Tekeli et al. [ii] have investigated the wear property of Fe-0.3%C P/M steel at various heat treatments. They have found that the annealed specimens are subjected to lower wear rate compared to as-sintered specimens. Ozkangulsoyet al. [iii] have studied the triobological behaviour of different percentages of boron added iron based P/M alloys. They have found that the boron addition results in decreasing the wear rate of alloys and also observed that the plastic deformation with delamination of surface layers at the subsurface initiated by the cracks on worn out surface.

Kandavel et al. [iv] have analysed the wear behaviour of the sintered Fe-C-Cu-Mo P/M alloy steels and have found that the addition of alloying elements such as Cu and Mo invariably enhances the wear resistance of the alloy steels. They have also observed that the delamination wear mechanism is predominant in the alloy steels. Dhanasekaran et al. [v] have carried out research work to study the influence of Ni addition to Fe-C-Cu alloy steels on wear property. They have reported that the Ni addition not only enhances wear resistive property and also increases the frictional coefficient during sliding wear test. Sudhakar et al. [vi] have studied the wear behaviour of Fe-0.2% Ni -0.47%C and Fe-0.2%Ni-0.2%C (P/M) alloy materials at various heat treatments. They have observed that the delamination wear is predominant in as sintered and oxidative wear is dominant in hardened and tempered specimens. Wang et al. [vii] have studied the tribological behaviour of copper added titanium alloy using ZrO_2 as counter-face material. They observed that the Cu addition invariably enhances the wear resistance of the alloy steel and both adhesive and abrasive wear are observed to be common wear mechanism in the material. Qiu et al. [viii] have conducted dry sliding wear tests on Ti-47Al-2Cr-2Nb-0.2W (at. %) alloy at four different environments using zirconia as a counter-face disc for the tribological study [7]. They have found that the oxygen environment exhibits lower wear rate and hydrogen environment has a little effect on wear rate. Jun'anwang et al. [ix] have studied the influence of heat various treatments on wear property of Fe-1%C-3.5%Mo alloy steel and have reported that the quenched and tempered specimen is subjected to higher wear coefficient compared to the as-sintered specimen. They have also stated that the alloy steel exhibits low and stable wear rate. Tekeli et al. [x] have analyzed the tribological behaviour of Fe-C-Ni steel under various heat treatments. They have found that the inter-critically annealed specimen exhibits higher hardness and strength than that of other heat treated specimens. Anton et al. [xi] have investigated the tribological behaviour of sintered steels with high content of manganese-nickel and have found that the addition of C and Mn increases the wear resistance property of the alloy steel. Colaco et al. [xii] have studied the wear behaviour of AISI M42 HSS material under various sintering techniques. They have found that the abrasive wear resistance of laser melted and tempered alloy steel is lower than the as sintered material. LorellaCeschini et al. [xiii] have investigated the wear behaviour of Fe-C-Mo and Fe-C-Cr P/M alloy steel at various sintered temperatures. They have reported that Mo alloyed steel is observed to have more hardness than the other alloy steel and mild oxidative wear is found as common wear mechanism at lower load and delamination wear is common at the higher load conditions for the alloy steels. Kandavel et al. [xiv] have studied the plastic deformation and densification of Fe-C-Cu-Mo-Ti sintered alloy steels. They have stated that the addition of alloying elements invariably enhances the hardness of alloy steel, which in turn may enhance wear resistance of the alloy steels. Straffelini et al. [xv] have analyzed the wear behaviour of steam treated Fe-2%Cu and Fe-0.3%C P/M alloys. They have observed delamination wear at lower sliding speed and combination of both delaminative and oxidative wear at the higher sliding speed.

2 EXPERIMENTAL DETAILS

Elemental powders of atomized iron (Fe), graphite (C), and titanium (Ti) were weighed accurately and homogeneously mixed in a pot mill to compose an alloy powders of Fe-1%C, Fe-1%C-1%Ti, then compacted into cylindrical billets of size Ø25×33mm using suitable cylindrical die-punch set in a 100T capacity hydraulic press. During compaction graphite plus oil used as a lubricant and hydraulic load of 18T (180kN) was gradually applied on it to obtain 85% theoretical density for the green compacts of alloy steel. The indigenously prepared ceramic coating was applied over exposing surface of green compact specimens to prevent the surface oxidation during sintering process. Sintering is carried out in a 3.5 kW muffle furnace at a temperature of 1100 °C ±10 °C for a period of 30 minutes and samples are left in the furnace to cool. The sintered specimens were once again heated to a temperature 1000 °C and hot upsetting was carried out on the heated specimens to convert it into square rod of size 10X75mm. Then, the machining operation was carried out on square specimens to get standard wear test specimens of size (Ø6 mm × 50 mm). The contact surface of the pin was polished to conduct dry sliding wear tests using pin-on-disc Tribometer. EN31 hardened steel disc (53.5 HRC) was used as a counter-face material for all the wear tests. The wear test was conducted by keeping the pin at a track radius of 17 mm and maintained constant for the entire dry sliding wear tests. The wear experiment was carried out as per the standard ASTM G99-05. The D-optimal design on response surface methodology by Design Expert (DE) software was used to plan the experimental test and the tests were carried out based on the test plan provided by the DE software. In the present work, the load and speed are considered as input parameters and mass loss and coefficient of friction are considered as output parameters. The load was set at the range 15-50 N and speed was set at 300-1200 rpm and keeping the time (30 min) constant for the entire dry sliding wear tests. The test plan of the experiment is illustrated in Table 1. The wear loss is calculated by measuring the mass of pin before and after the tests using four decimal Shimadzu digital balance (Made in Japan). The coefficient of friction was obtained from the computer system interface with the tribometer. The optical and micro structure images were captured by KYOWA, ME-LUX2, microscope fitted with CCD camera. SEM images of maximum worn out specimen was captured by using JEOL-Field Emission Scanning Electron Microscope (TSM-6701F, Japan).

TABLE 1. WEAR TEST PLAN FOR P/M ALLOY STEELS

Runs	Load (N)	Speed (rpm)
1	15	300
2	26.67	300
3	50	300
4	50	600
5	32.5	750
6	15	900
7	15	1200
8	26.67	1200
9	50	1200

3 RESULTS AND DISCUSSION

A. HARDNESS OF P/M ALLOY STEEL

Compositions	As-sintered (HV)	Hot upsetting (HV)
Fe-1%C	167.5	247.5
Fe-1%C-1%Ti	204.5	302.5

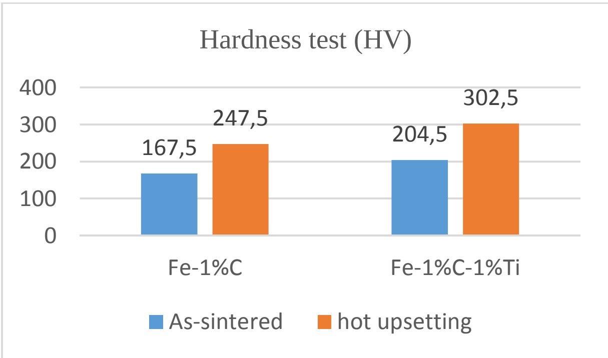

Fig. 1 Hardness test for both as-sintered and hot upsetting specimens

The density of hot upset specimen has been increased significantly due to the pores closure of as sintered preforms during the upsetting process irrespective of the alloy steels. Addition of Ti to the plain carbon steel is also attributing for the enhanced hardness in the alloy steel. Titanium is one of the known alloying elements to enhance the hardness the material. The possible formation of TiC during sintering process could also contribute for further enhancement of hardness in the material [14].

B. MASS LOSS BEHAVIOUR OF P/M ALLOY STEELS

The mass loss is one of the important response factors for wear studies. In machinery, each component has a relative motion with another and in long period the wear loss due to friction with matting parts affect the normal functioning of the component. It is essential that the study on wear behaviour for any material is warranted. The wear characteristics of P/M material is a complex phenomenon due to the presence of pores at the contact surfaces. Table 3 provides the experimental results of P/M alloy steels. The mass loss behaviour of the plain carbon steel is shown in Fig. 2(a) & 2(b). The mass loss trend is similar with respect to load and speed of the wear tests for the plain carbon steel. The maximum wear loss (0.0103g) is exhibited at the highest load/speed conditions. As the mass loss is continuously increasing with increase in load and speed, it is understood that the delamination wear has occurred in the plain carbon steel during the wear test. The wear loss characteristics of Ti added plain carbon steel is depicted in Fig. 2(c) & 2(d). Though the similar kind of trend is exhibited by the specimen as like the plain carbon steel, the mass loss values are significantly reduced in the alloy steel. Addition of Ti plays vital role in reducing the mass loss in the P/M alloy steel, on the other hand Ti addition significantly improves the wear resistance of the alloy steel [7]. The maximum mass loss (0.0036g) has occurred at the highest load and speed conditions.

There is possibility of formation of carbides of alloying element during sintering process, which could attribute in increasing the hardness and there by wear resistance too in the alloy steel.

C. Coefficient of friction of P/M alloy steels

Fig. 3(a) & 3(b) illustrate the frictional coefficient behaviour of the plain carbon steel during wear test. Initially, the friction between the contact surfaces are more, and it is declining with increase in load and mounting up with increase in speed. It is observed from the plot that the minimum frictional coefficient is exhibited at the highest load irrespective of the speed. Due to delamination wear character, the frictional coefficient is continuously varying in the plain carbon steel. The coefficient of friction characteristics of Ti added plain carbon steel is shown in Fig. 3(c) & 3(d). Though the trend seems like a base metal, the friction coefficient exhibited by the alloy steel is higher. It is observed from the plots that the frictional coefficient is higher for a particular value of load and then descending to the minimum irrespective of speed. The higher frictional value is due to the presence of carbides in the alloy steel. At the higher load the contact surface becomes polished, which in turn reduces the friction during wear test.

TABLE 3. EXPERIMENTAL RESULTS OF P/M ALLOY STEELS

Run	Load (N)	Speed (rpm)	Time (min)	Mass loss (g) Fe-1%C	Coefficient of friction(μ) Fe-1%C	Mass loss (g) Fe-1%C-1%Ti	Coefficient of friction(μ) Fe-1%C-1%Ti
1	15	300	30	0.0017	0.6186	0.0004	0.6331
2	26.67	300		0.0031	0.5316	0.0013	0.5893
3	50	300		0.0083	0.4747	0.0029	0.4389
4	50	600		0.0092	0.4989	0.0033	0.4634
5	32.5	750		0.0075	0.5258	0.0025	0.5603
6	15	900		0.0069	0.5973	0.0019	0.6236
7	15	1200		0.0078	0.6004	0.0024	0.6193
8	26.67	1200		0.0089	0.6281	0.0031	0.653
9	50	1200		0.0103	0.4653	0.0036	0.3513

D. Empirical equation for mass loss and coefficient of friction

Generalized mathematical equation of wear behaviour of P/M alloy steels for mass loss and coefficient of friction corresponding to the speed and load has been generated from the ANOVA module of design software [4]. The equations are as follows: The generalized equations of mass loss (Z_{ML}) and coefficient of friction (Z_{μ}) for Fe-1%C are given in the equations (A) and (B).

$$Z_{ML} = (-4.76539\times10^{-3}) + (1.55835\times10^{-5}\times X) + (1.57529\times10^{-4}\times Y) - (1.32808\times10^{-7}\times XY) - (4.157693\times10^{-9}\times X^2) + (1.02108\times10^{-6}\times Y^2) \quad \text{- (A)}$$

$$Z_{\mu} = +(0.65793) - (6.43088\times10^{-5}\times X) - (3.13871\times10^{-3}\times Y) - (7.74573\times10^{-7}\times XY) + (7.2853\times10^{-8}\times X^2) + (1.57865\times10^{-6}\times Y^2) \quad \text{- (B)}$$

The generalized equations of mass loss (Z_{ML}) and coefficient of friction (Z_{μ}) for Fe-1%C-1%Ti are provided in the equations (C) and (D)

$$Z_{ML} = -(1.83012\times10^{-3}) + (3.30194\times10^{-6}\times X) + (9.95656\times10^{-5}\times Y) - (4.453\times10^{-8}\times XY) - (1.85802\times10^{-10}\times X^2) - (2.0927\times10^{-7}\times Y^2) \quad \text{- (C)}$$

$$Z_{\mu} = (0.53559) + (5.39802\times10^{-5}\times X) + (7.66825\times10^{-3}\times Y) - (3.35787\times10^{-6}\times X\times Y) + (1.85296\times10^{-8}\times X^2) - (1.73736\times10^{-4}\times Y^2) \quad \text{- (D)}$$

Where, X- speed (rpm) and Y- load (N). Based on these empirical correlations the mass loss and friction coefficient of alloy steels could be evaluated at any load and speed. From the equations (A),(B), (C) and (D), the response parameters the P/M alloy steels are calculated and tabulated (Table 4) for comparison with the experimental results. It is understood from the comparison that the degree of accuracy between the experimental results and the results obtained from the mathematical correlation.

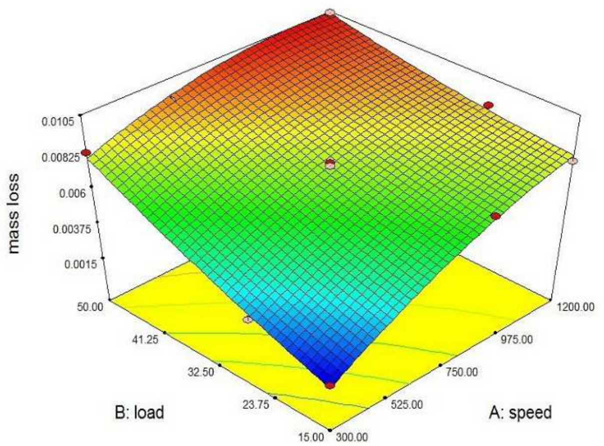

Fig.2 (a) 3D-plot graph for Fe-1%C

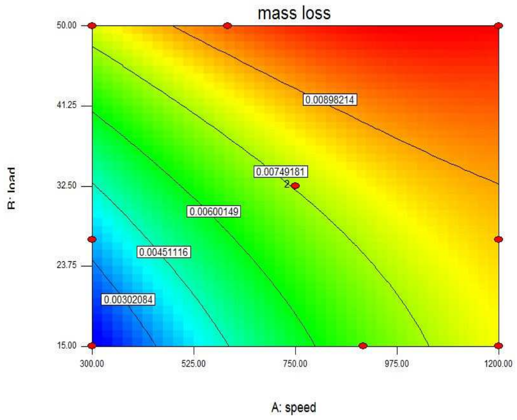

Fig.2 (b) 2D- contour surface plot graph for Fe-1%C

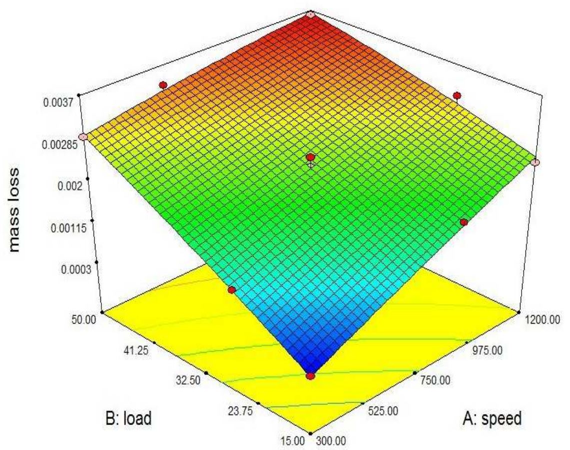

Fig.2 (c) 3D-plot graph for Fe-1%C-1%Ti

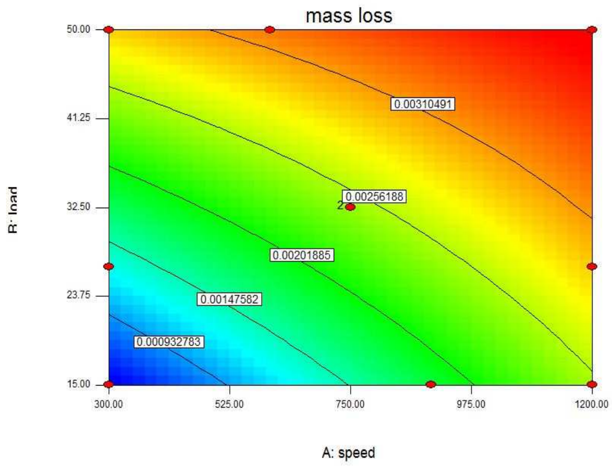

Fig.2 (d) 3D-plot graph for Fe-1%C-1%Ti

Fig. 2 (a) - (d) wear behaviour on P/M alloy steels at various speeds and loads

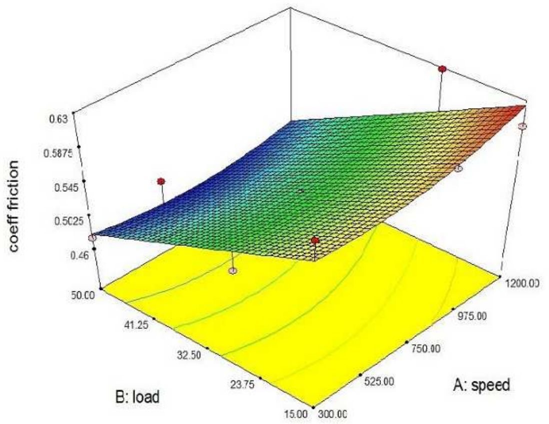

Fig. 1. Fig.3 (a) 3D-plot graph for Fe-1%C

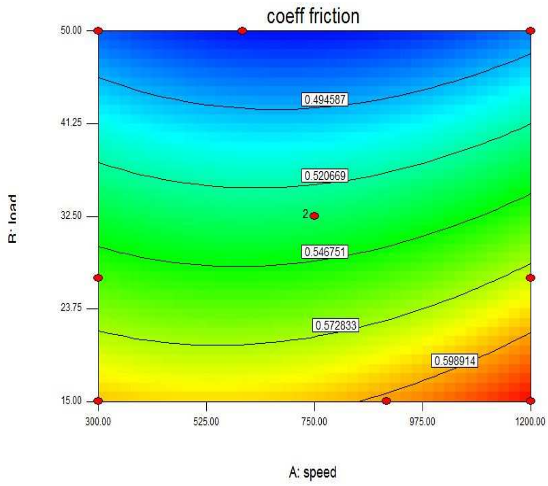

Fig. 2. Fig.3 (b) 2D- contour surface plot graph for Fe-1%C

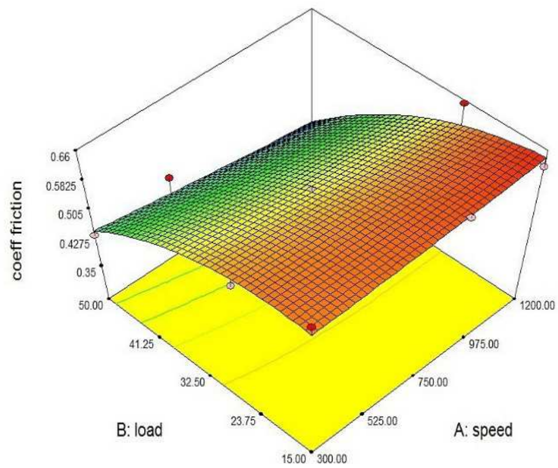

Fig.3 (c) 3 D –plot graph for Fe-1%C-1%Ti

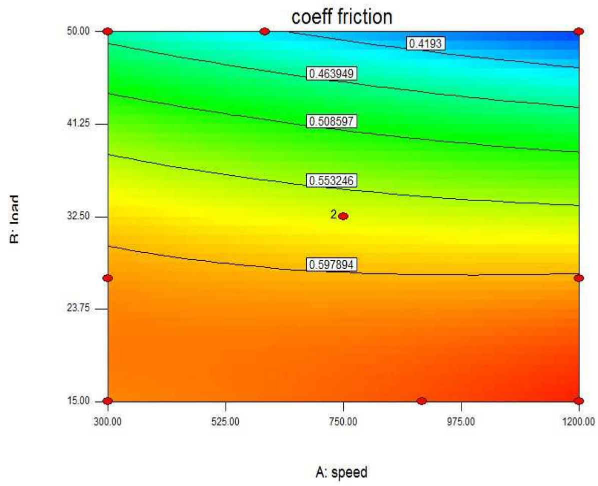

Fig.3 (d) 2D –contour surface plot graph for Fe-1%C-1%Ti

Fig. 3 (a) - (d) Coefficitent of friction on P/M alloy steels at various speeds and loads

TABLE 4. PREDICTED VALUES OF P/M ALLOY STEELS.

Composition of alloy	Speed (rpm)	Load (N)	Mass loss (g)	Coefficient of friction (μ)
Fe-1%C	750	32.5	0.0075	0.5314
Fe-1%C-1%Ti			0.0024	0.5703

E. X-RAY DIFFRACTION AND MICROSTRUCTURE

1. XRD analysis:

XRD has been taken on wear debris of the alloy steels. The wear debris was collected after the wear test and was crystal structures. It is found from the wear debris analysis that the higher amount of Fe, and lesser amount of C and Ti is present in the wear debris. Fig.4 (a) & 4(b) are the XRD peak analysis for wear debris of the plain carbon steel and Ti added P/M alloy steels respectively. It is observed from the images that iron (Fe), carbon (C), iron Carbide (Fe_2C), titanium carbide (Ti_2C) are present in the wear debris. Iron and carbon display cubic structures and Iron carbide (Fe_2C) in various forms such as orthorhombic and hexagonal crystal structures. Titanium carbide (Ti_2C) display a hexagonal crystal structures.

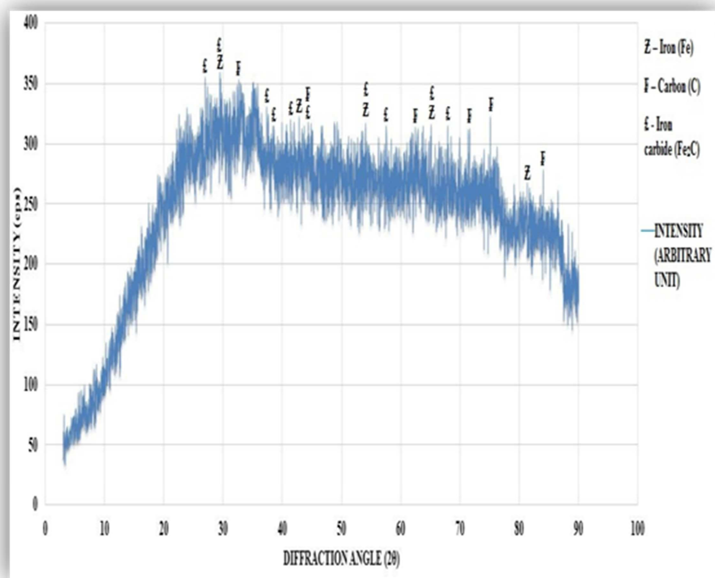

Fig.4 (a) XRD peak analysis on wear debris of Fe-1%C

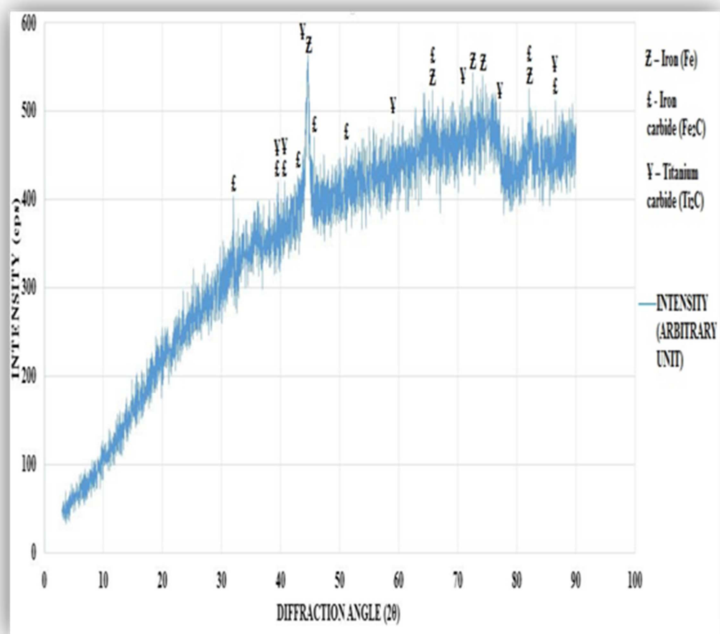

Fig.4 (b) XRD peak analysis on wear debris of Fe-1%C-1%Ti

2. *Microstructure:*

The microstructure of plain carbon steel and Ti added P/M alloy steels are depicted inFig.5 (a) & 5(b) respectively. The basic microstructure for both the alloy steels is Ferrite-pearlite. The microstructure of the Fe-1%C is shown in Fig. 5(a). Ferritic grains are clearly visible and pearlites are embedded on ferrite matrix. Iron carbide is also appeared in the image. Needle structure is also visible in random and is due to the hot upsetting of the preforms for making a tensile test specimen. Fig. 5(b) shows the micro image of Ti added plain carbon steel. Ferritic and pearlitic structure is observed in the image. The formations of TiC and FeC during sintering are also appeared in the image of the alloy steel. Tiny pores are seen sparingly. The presence of carbide of alloying element promotes the wear resistance of the alloy steel and at the same time it offers more frictional coefficient.

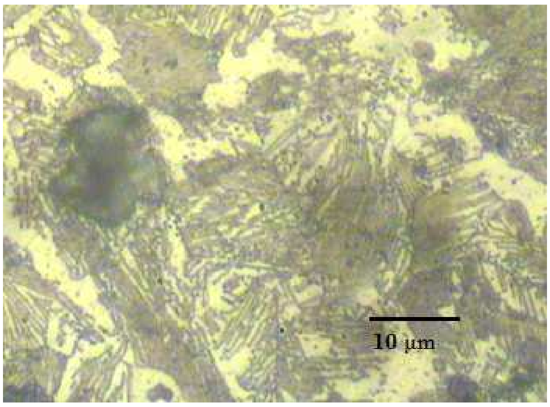

Fig.5 (a) Fe-1%C

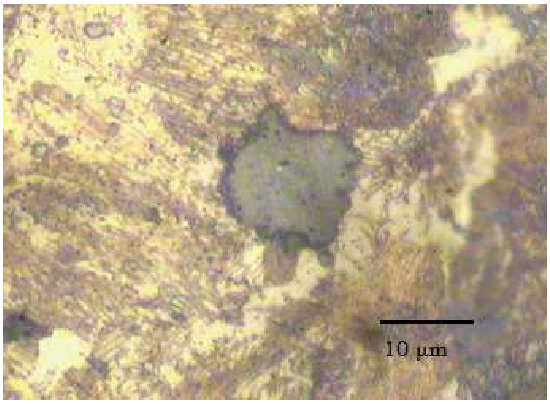

Fig.5 (b) Fe-1%C-1%Ti

F. WEAR PATTERN AND SEM IMAGES OF MAXIMUM WORN-OUT SPECIMENS :

The wear patterns of maximum worn out specimen of alloy steels are shown in Fig. 6(a) & 6(b). The wear pattern for the plain carbon steel is depicted in Fig. 6(a). It is understood from the wear pattern that the material is subjected to uniform wear and the wear loss is also higher as the image shows the wide wear track. Fig. 6(b) shows the wear pattern of Ti added alloy steel. The wear track appeared in the image is smaller in width; this is due to the higher resistance of alloy steel against the wear. The image is also exhibiting non-uniform wear pattern, could be due to the presence of carbides of alloying elements.SEM images of contact surfaces of test specimens are shown in Fig. 6(c) & 6(d). Fig. 6(c) shows the SEM image of the plain carbon steel. The plain image in the figure shows the uniform wear over the entire region of the contact surface. The oxides chemical element is appeared as white patches in the image. Iron carbides are appeared at some places. Micro pores are observed randomly in the image. Fig. 6(d) depicts the SEM image of Ti added alloy steel. It is clearly understood from the image that the specimen is subjected to non-uniform wear in the test. The wear loss has occurred at the soft region of the contact surface and the minimum wear has occurred at the carbide formed regions, which makes the wear pattern non-uniform for the alloy steel. The carbides of alloying elements are appeared as black patches at some places. The oxide of material is also visible as small white patches in the image. The formation of carbides due to alloying elements attributes for improving the hardness and wear resistance of the alloy steel.

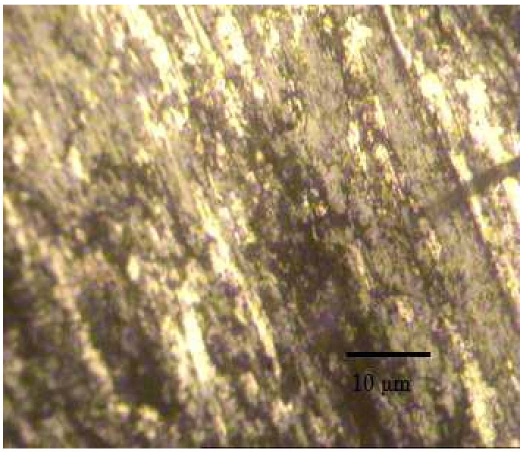

Fig. 6 (a) maximum wear on worn-out surfaces of Fe-1%C

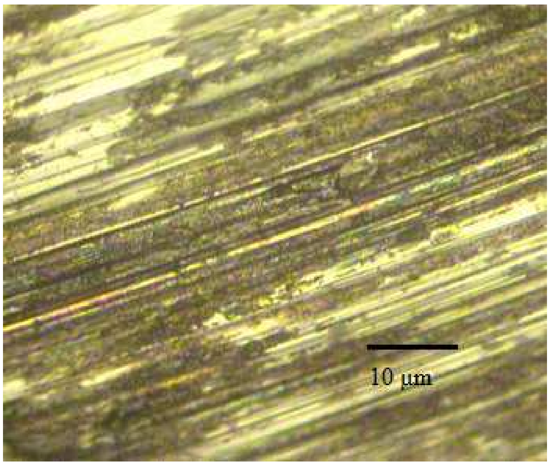

Fig. 6 (b) maximum wear worn-out surfaces of Fe-1%C-1%Ti

In SEM image and wear pattern image of Ti addition is decreases the wear rate and coefficient of friction on higher load due to formation on worn-out surfaces delamination of thin layer of oxide formation [7], [4].

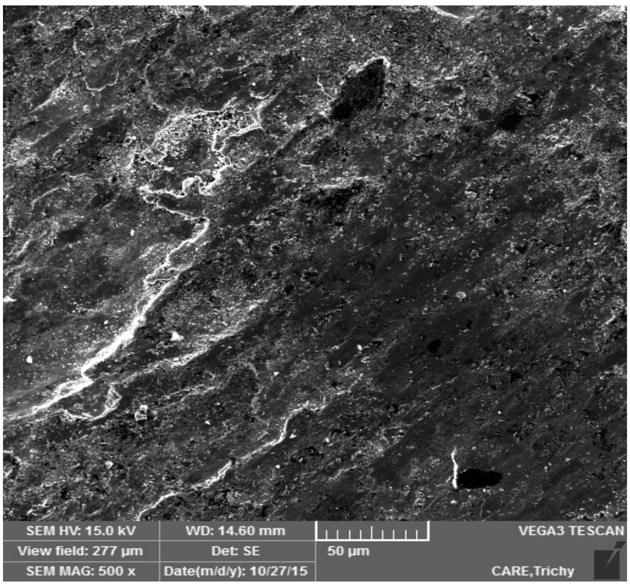

Fig. 6 (c) SEM image on worn-out surfaces of Fe-1%C

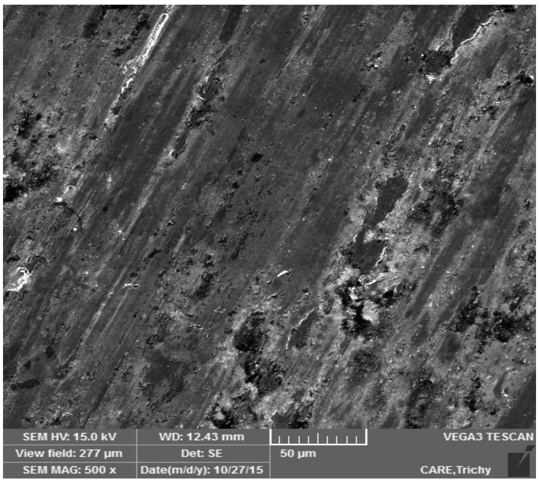

Fig. 6 (d) SEM image on worn-out surfaces of Fe-1%C-1%Ti

4 CONCLUSION

Based on the dry sliding wear tests to study the wear characteristics of the P/M plain carbon steel (Fe-1%C) and Ti added plain carbon steel (Fe-1%C-1%Ti) the following conclusions could be arrived.

1. The plain carbon steel (Fe-1%C) exhibits higher mass loss and lower frictional coefficient.
2. 1%Ti addition to the plain carbon steel significantly enhances the wear resistance and hardness of the alloy steel due to the formation of carbides.
3. The formation hard phase (TiC) invariably increases the friction coefficient of the Ti added alloy steel.
4. The delamination wear mechanism is observed for both the alloy steels.
5. The generalized mathematical correlations are generated to find the mass loss and coefficient of friction for the alloy steels and also validated with the experimental results.
6. The plain carbon steel is containing Ferritic-Pearlitic microstructure and iron carbides is placed at some places in the microstructure. Ti added alloy steel contains TiC along with other micro phases appeared in the plain steel.
7. Titanium added alloy steel is subjected to non-uniform wear due to the formation of hard phases.

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