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Investigations on dry sliding wear behaviour of Sintered/Extruded P/M Alloy Steels (Fe-C-W-Ti)

S. Senthur Prabu[a*], S. Prathiba[b], Asokan M.A[a], Anshul Jain[a], Neeraj Kumar Jain[a], Pratyush Kumar Chourasiya[a]

[a]*School of Mechanical and Building Sciences, Vellore Institute of Technology, Vellore – 632014, India*
[b]*Department of Chemical Engineering, St.Joseph's College of Engineering, Chennai -600119, Tamil Nadu, India*

Abstract

Powder Metallurgy (P/M) is an established manufacturing process allows components of complex geometries with tailor-made strength and high tolerances to be produced in one single operation without subsequent machining resulting in low cost and low environmental impact. Thus, it has replaced all traditional methods of metal forming operations because of added advantages like lesser energy consumption, maximum material utilization, low relative material wastage, and competitive cost. Sintered low alloy steels find numerous applications in making components for machine parts, automobile parts, structural components, etc. Properties and microstructures obtained using P/M that can't be obtained by alternative metal working techniques. The final density of the sintered P/M parts plays a vital role in determining the component properties and characteristics. In the present study, an attempt has been made to investigate the dry sliding wear characteristics of sintered/hot extruded P/M alloy steels with Fe-1% C as base material, W (Tungsten) and Ti (Titanium) as alloying elements. The wear behavior of the sintered/hot extruded performs were studied under dry sliding conditions on pin-on- disc (ASTM G99) arrangement against EN 38 steel disc of hardness HRC 60 with a constant sliding speed of 2m/s and at a normal load of 30, 50 and 70N respectively. The microstructure and wear regime of extruded P/M steels has been systematically characterized to understand the structure-property relationships using both optical microscopy and scanning electron microscope (SEM). Addition of W and Ti significantly enhances the wear resistance of the extruded P/M plain carbon alloy steel due to the presence of WC (tungsten carbide) and TiC (titanium carbide). The microstructure reveals a combination of Widmanstatten type ferrite on both the extruded P/M steels. Coefficient of friction is slightly higher due to presence of second phase hard WC in tungsten alloyed plain carbon steel. Delaminative wear mechanism is commonly found in both extruded P/M steels with an increase in applied load.

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Keywords: P/M alloy steels; Wear loss; Sliding distance; Coefficient of friction

*S. Senthur Prabu. Mobile: +91 9842210982
E Mail: senthurprabu.s@vit.ac.in

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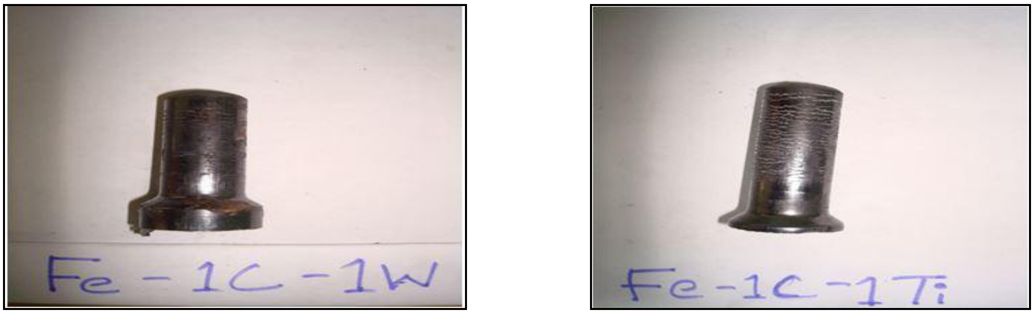
1. Introduction

Powder Metallurgy (P/M) manufacturing process is one of the emerging fields for the production of steels, having immense potential for industrial applications, in response to the requirements of mass production, lean manufacturing, and improved reliability. Producing steels through the route of P/M has wide-spread applications in the fields of automobiles, aerospace and manufacturing. These components usually face working-conditions involving abrasion, rolling and sliding, making it important to study the wear phenomenon. The mechanical properties here mainly depend on the final density of sintered P/M alloys. Sinter-hardening of P/M components is an established cost-effective process to produce high strength parts. Residual porosity after sintering is detrimental to the mechanical properties of the sintered materials. The presence of voids or porosity in compacted preforms and sintered products is one of the major factors causing reduction in its mechanical properties of P/M alloys. Porosity may contribute to strength degradation in two ways. First, pores will act as local stress concentrators, and second, they may act as crack precursors. Salak et al. [1] investigated that the nature of the porosity is controlled by several processing variables such as green density, sintering temperature and time, alloying additions, and particle size of the initial powders. The strengthening of sintered P/M low alloy steels can be achieved through densification, alloying and heat treatment. Vardavoulias et al. [2] studied the sliding-wear behaviour of ceramic-reinforced high-speed P/M steel. The wear behaviour of sintered high-speed steel-type particulate composites depends significantly on microstructural parameters, such as those of the metallic matrix and primary carbides, and also on certain additional parameters related to the P/M process. Pin-on-disc test results, coupled with SEM observation of the wear tracks and microstructure image analysis, indicated the prominent role of the added ceramic particles. More precisely, the size, the mechanical resistance and the cohesion with the metallic matrix of TiC, uncoated Al_2O_3, and TiN-coated Al_2O_3 particles, largely determine the wear behaviour of such materials. In addition, the roles of the residual porosity and of the presence of copper as a solid lubricant are pronounced in this investigation. Tekeli et al. [3] studied dry sliding wear behaviour of Fe-0.3%C-2%Ni powder metallurgy processed (P/M) steels at constant sliding speed, load and distance. One of the sintered specimens was quenched- tempered and others intercritically annealed. Wear tests under dry sliding conditions using a pin-on-disk showed that hardness and wear strength in intercritically annealed specimens were higher than that of quenched-tempered specimen. Various heat treatments affect the microstructure and dry sliding wear behaviour of iron based powder metallurgy steels. Khorsand et al. [4] investigated that delamination wear mechanism of sintered steel is similar to that of conventional wrought or cast materials. But, in sintered material, open porosity acts as sites of generation and collection of wear debris or formation of subsurface cracks. Wear rate is decreased and fatigue strength is increased by heat treatment. Fodor et al. [5] reported that the effect of carbon addition on the microstructure of mixed elemental powder alloy systems cooled at moderate rates after sintering and concluded that at moderate cooling rates the amount of martensite increases with increase in carbon content (0.5% to 0.8%) and the amount of martensite is doubled during furnace hardening. Salahinejad et al. [6] studied the microstructure and dry sliding wear characteristics of a porous Cr-Mn-N P/M austenitic stainless steel, sintered and water-quenched (subsequently). The densification of the mechanically alloyed 18Cr-8Mn-0.9N stainless steel powder is performed by sintering at 1100°C for 20 h and subsequently water-quenching. The porous nano-structured austenitic stainless steel with a relative density of 85% so developed exhibited an outstanding wear resistance compared with AISI 316L stainless steel samples attributed to its considerable intrinsic hardness and its specific configuration of pores. Uzunsoy et al. [7] studied the wear behavior of P/M 316L stainless steel with additions of 0.6 wt. % elemental powder. The wear test of the samples is conducted using a pin specimen of P/M 316L stainless steel doped with elemental boron against a steel disc specimen with hardness of 180 (HV10). Densification achieved was up to 95% of theoretical density. Mechanical properties were improved with boron addition, with decrease in wear rate. The abrasive-induced delamination wear dominated at the samples. SEM observations of the worn surfaces revealed that plastic deformation occurred with delamination of surface layers in the sintered conditions. Wang et al. [8] investigated and compared that the sintering processes of preforms by varying the variables such as sintering temperature, initial density and preforms design used for fabrication of steel parts for various powder forging processes. The type of wear evident in most of the P/M alloyed sintered steel may be oxidation wear, adhesive wear, and abrasive wear and melt wear depending on the wear conditions. Lorella ceschini et al. [9] reported the wear behaviour of sintered steel under both dry sliding and abrasive conditions and concluded that the best behaviour was observed for the more hardenable steel, under dry sliding conditions giving rise to bainitic microstructures and the sintering temperature along with compacting pressure plays a determining role improvement of the resistance to sliding wear. Alloying the steel with W increases strength by forming second-phase carbides (Tungsten forms carbides if there is enough carbon and absence of stronger carbide forming element), and it also increases the melting point. Ti is a strong carbide forming element; it fixes carbon in inert particles. Senthur prabu et al. [10] investigated that the dry sliding wear behaviour by addition of tungsten in the plain carbon steel and resulted that the wear resistance of the P/M low alloy steel gets significantly enhanced. In view of the potential applications of low alloy P/M steels as wear resistant components, it becomes significant to study the wear behaviour in order to evaluate their suitability for frictional wear applications. Also the final density of the sintered P/M parts plays a vital role in determining the component properties and characteristics. The present investigation is mainly focused on the dry sliding wear characteristics of sintered/hot extruded P/M alloy steels with Fe-1% C as base material, W and Ti as alloying elements under dry conditions on pin-on disc arrangement against EN 38 steel disc of Hardness HRC 60 with a constant sliding speed of 2 m/s and at a normal load of 30, 50, 70 N respectively.

2. Experimental Details

Elemental powders of Iron(Fe) powder of particle size 150µm, Graphite(C) powder of particle size 5µm, Tungsten(W) powder of 100 µm and Titanium(Ti) powder of 100 µm were accurately weighed and thoroughly mixed in an indigenously made pot mill for 10 hrs to yield the alloy compositions of Fe-1%C-1%W and Fe-1%C-1%Ti. The basic characteristics of elemental alloy powder such as flow rate, apparent density, tap density, and flowability has been carried out using standard methods of testing are exhibited in **Table 1**. The mass of blended powder was then compacted into cylindrical billets of size Ø25X33mm using a hydraulic press of 1000 kN capacity. During compaction graphite was used as lubricant. After the compaction, indigenously made aluminum ceramic coating was applied over the exposing surface of green compacts immediately to avoid oxidation and dried for 24h. The coated and well dried compacts were sintered using 3.5kW capacity muffle furnace at 1100 ± 10^{o}C, for a period of 120min, in nitrogen purged inert atmosphere to avoid oxidation. Hot extrusion process was performed on the sintered preforms at a temperature of 1050˚C to get cylindrical pin of 10 mm diameter as shown in the **figure 1**. Subsequently the hot extruded specimens machined off to obtain the standard size of 6mm diameter. Disc polishing was made before the specimens subjected to wear test. The initial weight of the steel pin was measured after cleaning in acetone followed by drying using an electronic weighing balance of 0.01 mg accuracy. Computer assisted Pin-on-disk tribometer was used to carried out dry sliding wear tests on P/M alloy steel pins against counter face EN 38 steel discs of Hardness HRC 60. The disc was cleaned by acetone before and after the commencement of wear tests to get the high precession results. The dry sliding wear tests were conducted at a normal load of 30, 50 & 70N with a sliding speed of 2m/s. The material mass loss was determined as the change in weight of the sintered/extruded steel pin measured accurately before and after the wear test. Coefficient of friction was also taken during the wear test from the tribometer. The wear mechanisms were studied by observing the worn out surfaces using both optical microscope and SEM.



(a) (b)

Figure- 1 Extruded P/M alloy steels (a) Fe-1%C-1%W; (b) Fe-1%C-1%Ti

Table 1 Physical properties of elemental mixed powder of alloy

Composition	Theoretical Density (g/cc)	Apparent Density (g/cc)	Tap Density (g/cc)	Flowability (s/g)
Fe-1 % C-1% W	7.72	3.07	3.48	0.53
Fe-1 % C-1%Ti	7.62	3.05	3.46	0.52

3. Results and Discussions

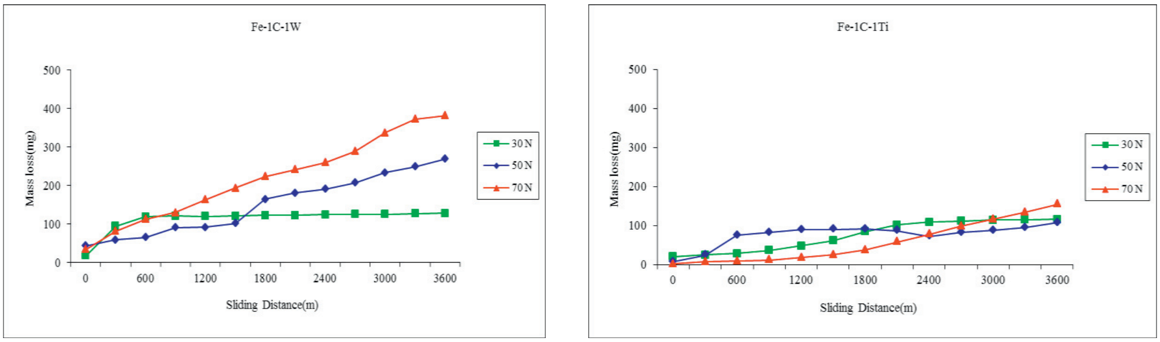
Basic dry sliding wear curves (wear loss and frictional coefficient versus sliding distance) of sintered/hot extruded tungsten, titanium alloyed plain carbon steel (Fe-1%C-1%W, Fe-1%C-1%Ti) at constant sliding velocity of 2m/s for an axial load of 30, 50, 70N were obtained.

3.1 Wear behaviour of sintered/hot extruded Tungsten, Titanium alloyed plain carbon steel

The dry sliding wear behaviour of sintered /hot extruded tungsten, titanium alloyed plain carbon steel (Fe-1%C-1%W and Fe-1%C-1%Ti) is illustrated in **figure 2** (a-b).

The general principle of wear states that “the mass loss increases linearly with increase in applied load at irrespective of speed”. The same trend was observed in both the alloy steels, the amount of mass loss is lower at low level applied load of 30N because of oxide layer formed on the wear surface of the specimen intern reduces the wear. Whereas the wear rate for tungsten based extruded alloy steel rises abruptly above the applied load of 50N and that is apparent in 70N also. At higher loads and sliding speeds, sliding causes more oxidation due to the rise in interface temperature, as a result of heat generation due to the presence of the second phase hard tungsten carbide (WC), but the continuous fracture of the oxide layer results in higher mass loss during the wear test. The delamination wear was found to increase for a particular threshold value of load results increase in wear rates [11] also it is evident from the fig. 2(a).

From the plot 2(b) it was observed for titanium based P/M extruded alloy steel that the mass loss is minimum even with the higher load attribute due to the presence of titanium in the alloy, Ti is one of the known carbide former. The carbides of alloying element embedded along the grain boundaries leads to enhance the wear resistance of the extruded P/M alloy steel.

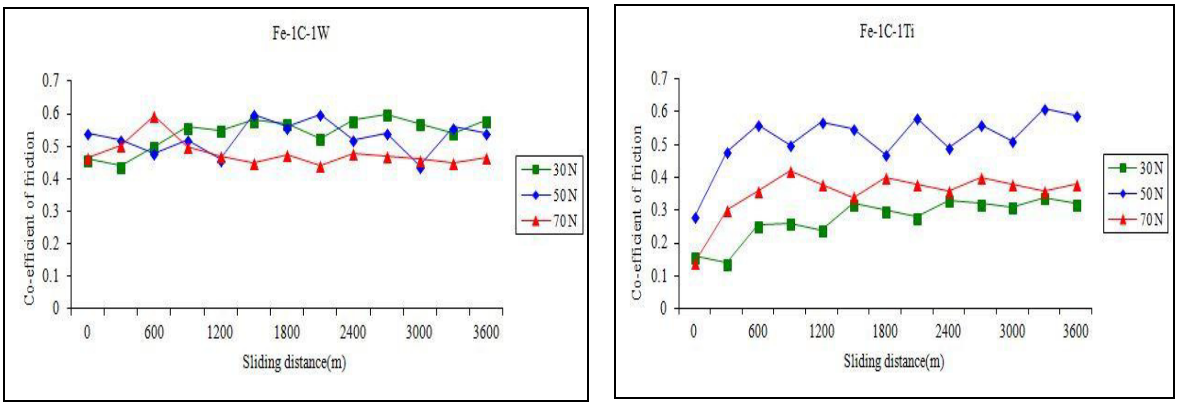


(a) (b)

Figure- 2 Dry sliding wear behaviour of extruded P/M low alloy steel at different loads (a) Fe-1%C-1%W; (b) Fe-1%C-1%Ti

3.2 Effects of applied load and sliding speed on the frictional coefficient

Figure-3 shows of the values of the steady-state friction coefficient measured for the extruded P/M low alloy steel at different loads. The values ranged from about 0.4 to 0.6 for Fe-1%C-1%W and for Fe-1%C-1%Ti varies from 0.12 to 0.6 gradually increasing as the sliding distance increases. In general frictional force is increasing with increase in axial load for the Ti alloyed steel. Whereas in the W alloyed steel the hard phase tungsten carbide contribute to increase in frictional force and also led to increase the wear rate of the alloy steel. From the plot 3(a) the frictional coefficient was observed to be high at the low level of applied load 30N. This may be due to the already formed oxide layer and hence the corresponding wear loss observed also lower. For the Fe-1%C-1%Ti alloy steel at the load of 50N the frictional coefficient is very high (0.6) because of the delamination of thin oxide film leading to the metal-to-metal contact at the interface result decrease in mass loss. Further incremental in applied load (70N) there was slight decline in friction coefficient for both the P/M alloy steels due to the oxide layer formed because of the higher interface temperature between the specimen and the disc material and reduce the direct metal contact [12] results in higher mass loss at higher load also it is evident from the figure 2(a & b).

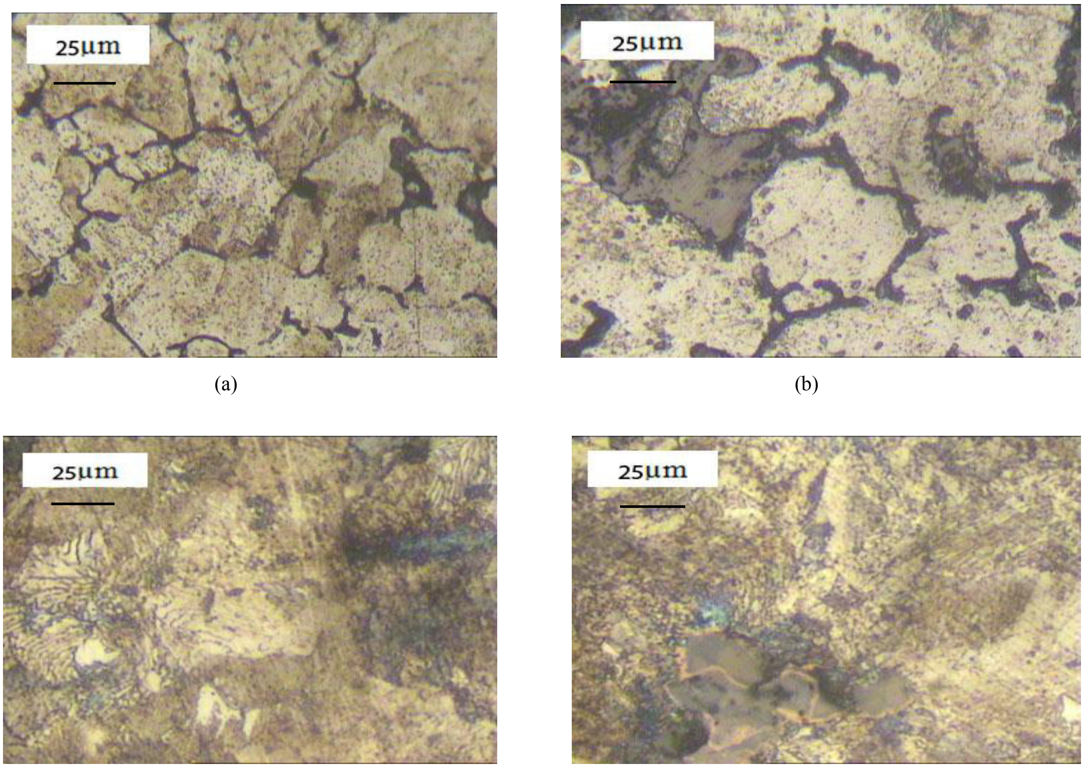


(a) (b)

Figure- 3 Variation of the frictional coefficient of extruded P/M low alloy steel at different loads (a) Fe-1%C-1%W; (b) Fe-1%C-1%Ti

3.3 Microstructure of as-sintered and extruded P/M alloy steels

The microstructures of the as-sintered and extruded P/M alloy steels are illustrated in figure 4 (a-d). W and Ti are one of the well-known carbide formers. The W and Ti carbides of alloying element embedded along the grain boundaries leads to enhance the wear resistance of both the extruded P/M alloy steels. Pearlites are uniformly distributed in the ferritic grain matrix in both the as-sintered alloy steels (fig. 4a & 4b). In Fe-1%C-1%W P/M extruded alloy steel (figure 4c) a mixed microstructure of Widmanstatten Ferrite and ferrite-cementite matrix (alternate lamellas) were found, it clearly indicated that might be possibly occurred at a high temperature between AC1and AC3 (723–900°C) attributes the higher hardness which increases thermal softening of the materials owing to temperature rise between the specimen and the disc material, results in higher mass loss at higher load whereas in the Fe-1%C-1%Ti alloy steel (figure 4d) shows a combination of Widmanstatten type ferrite, pearlite and bainite. Ti carbides embedded in between the ferrite–pearlite grains inturn decrease in mass loss compared to the extruded W alloy steel due to the second hard phase TiC but the frictional coefficient seems to be higher for Ti alloyed steel.



(a) (b) (c) (d)

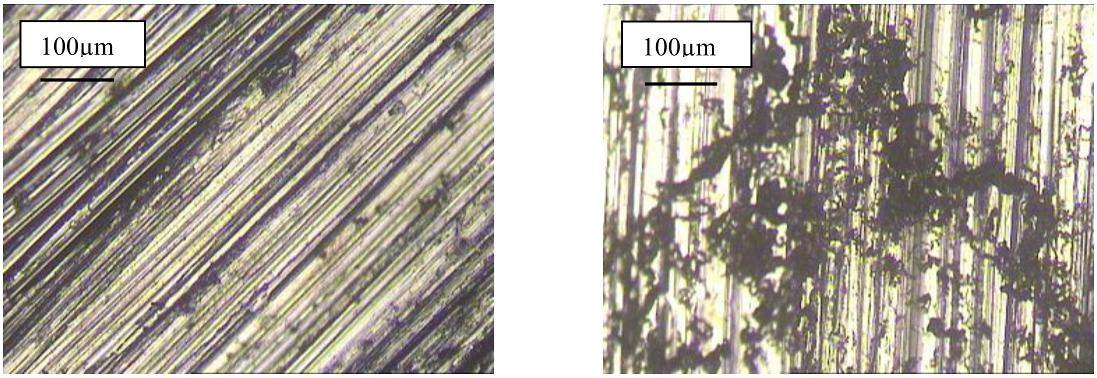
Figure- 4 Optical micrograph of the etched microstructures of sintered/extruded P/M alloy steels (a) Fe-1%C-1%W As-sintered; (b) Fe-1%C-1%Ti As-sintered; (c) Fe-1%C-1%W extruded; (d) Fe-1%C-1%Ti extruded

3.4 SEM images and wear pattern of the extruded P/M alloy steels

Figure 5 and **6** illustrates the optical microscopic and SEM images of wear pattern of the maximum worn out surfaces of the extruded P/M alloy steels specimens at maximum load of 70N.

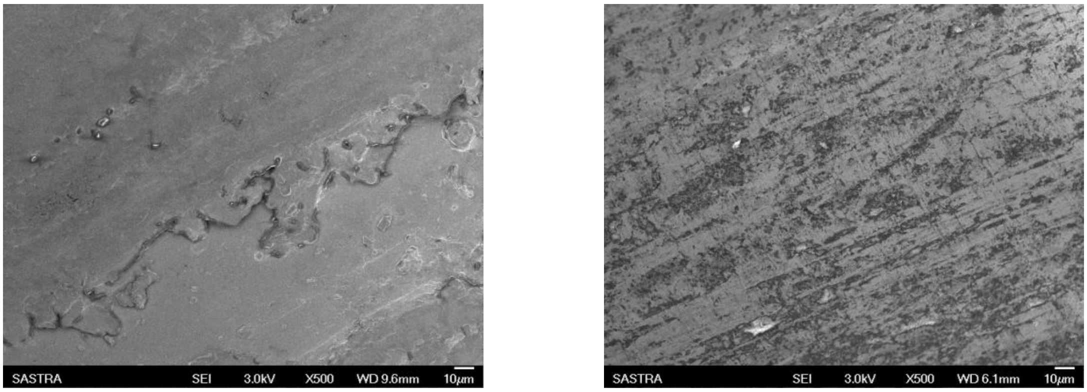
Non-uniform wear pattern was observed from the as-sintered Fe-1%C-1%W specimen whereas for the extruded specimen (figure 5a) shows the uniform wear pattern due to the presence of high dense tungsten carbides increases the Metallic wear due to the hardness of matrix and makes it more coherent results in thermal softening of the materials at the interface due to heat generation at high load causes more oxidation but that is counteracted by continuous fracture under those conditions results in the higher wear loss [8]. SEM image (figure 6a) exhibits small crater because of metallic wear due to secondary phase of WC increase the hardness of the matrix leads to increase in friction coefficient and also higher mass loss.

Figure 5b shows the wear pattern of the Fe-1%C-1%Ti alloy steel, Ti particulates embedded in between the ferritic grains matrix attributes the higher hardness causes the microchips, delamination flakes also evident from the SEM image (figure 6b). The delamination of thin oxide film increases the frictional coefficient at high load but inturn reduces the mass loss.



(a) (b)

Figure- 5 Wear pattern of maximum worn out of extruded P/M alloy steels (a) Fe-1%C-1%W; (b) Fe-1%C-1%Ti



(a) (b)

Figure- 6 SEM images of extruded P/M alloy steels wear track: (a) Fe-1%C-1%W; (b) Fe-1%C-1%Ti

4. Conclusion

The following points were concluded from the present investigation:

- The wear rate gradually increases with increase in applied load for both sintered/extruded P/M low alloy steels.
- In the Fe-1%C-1%W hard phase tungsten carbide contribute to increase in frictional force and also led to increase the wear rate at higher load due to the hardness of matrix results in thermal softening of the materials at the interface due to heat generation causes more oxidation but that is counteracted by continuous fracture of oxide film formed the metal to metal contact results in delamination wear.
- The frictional coefficient of Fe-1%C-1%Ti slightly decreases at higher load due to oxide layer formed because of the higher interface temperature between the specimen and the disc material and reduce the direct metal contact results in higher mass loss [12].
- The mixed microstructure of Widmanstatten ferrite and ferrite-cementite matrix (alternate lamellas) was observed in the extruded Fe-1%C-1%W alloy steels whereas in Fe-1%C-1%Ti extruded alloy steel shows a combination of Widmanstatten type ferrite, pearlite and bainite, which plays the vital role in the P/M alloy steels to enhance the wear resistance results in minimum mass loss compared to W based extruded alloy steel for a particular applied load.

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