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Influence of Titanium on dry sliding wear behaviour of sintered P/M low alloy steel (Fe-C-W)

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Abstract

Powder metallurgy (P/M) manufacturing process is one of the rapidly emerging fields and has extended the applications in aerospace, automotive, manufacturing industries replacing all traditional methods of metal forming operations because of its less energy consumption, maximum material utilization, low relative material wastage, low capital cost. The mechanical properties is mainly depends on the final density of sintered P/M alloys. The typical microstructure characteristics of sintered steel represent an important parameter affecting their wear behaviour. The present research work pertains to the study of dry sliding wear characteristics of sintered P/M Fe-1%C-1%W-1%Ti low alloy steel with different densities (85%, 90%, 95%), as they find several applications in manufacturing industries, particularly in automobile industries. These components usually face working-conditions involving abrasion, rolling and sliding, making it important to study the wear phenomenon. The wear behavior of the as-sintered preforms were studied under dry conditions on pin-on disc arrangement (ASTM G99) against EN 38 steel disc of Hardness HRC 60 with a sliding speed of 2 m/s and at a normal loads of 30, 50, 70N respectively. Wear mechanism of the worn out surfaces and microstructure of sintered P/M alloy steel has been characterized using both optical microscopy and SEM. Ferritic-pearlite microstructure are revealed from the as-sintered P/M alloy steels. Wear rate increases gradually with increase in porosity with respect to applied load. The main wear mechanism in the Ti alloyed P/M steel seems to be delamination wear in the higher load and oxidation wear at lower load. Failure by a delamination process is clearly indicated by the shape of the debris particles.

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1. Introduction

Powder metallurgy (P/M) involves the processing of metal powders. One of the major advantages of P/M is the ability to shape powders directly into a final component form. Using P/M techniques, high quality, and complex parts may be economically fabricated. There are also other reasons for using P/M techniques. Properties and microstructures may be obtained using P/M that cannot be obtained by alternative metal working techniques. The mechanical properties is mainly depends on the final density of sintered P/M alloys. The presence of voids or porosity in compacted preforms and sintered products is one of the major factors causing reduction in mechanical properties of P/M alloys. The final density of the sintered P/M parts plays a vital role in determining the component properties and characteristics. AminullIslam et al. [1] found that the wear rate gradually rises with porosity. Porosity adversely affects the pressure tightness (ability of a system to hold pressure), mechanical properties and wear resistance of components. The amount of porosity and the size and shape of pores have a great impact on material removal during wear. Below a certain critical pore size, wear occurs by two mechanisms: (i) partial covering of pores with a thin layer of deformed material and break-up on subsequent passes of the slider and (ii) nucleation of cracks at subsurface pores and connecting to other pores, this ultimately leads to delamination of wear particles. Porosity is a common feature of cast and sintered alloys steels and strongly influences their properties and applications. The presence of pores is accompanied by a decrease in mechanical Properties, i.e., a drop in strength and ductility of the materials [2]. Simchi et al. [3] studied the wear mechanisms of P/M alloy steel parts has similar properties compared to wrought materials, under the same tribological conditions, but the porosity plays a significant role in wear behaviour of alloy steels. Not only the total volume percentage of porosity influences the degradation of properties but also size, shape and interconnectivity of the porosity play an important role. The influence of porosity on the wear behavior of materials also depends on wear conditions. Pores act as lubricant reservoirs in wet sliding conditions, which provide considerable advantage in wear processes [4]. Wang [5] 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. Haynes [6] also reported that the strengthening of sintered P/M low alloy steels can be achieved through densification, alloying and heat treatment. Danninger et al. [7] investigated on sintered iron under different loads to establish the mechanical behaviour of sintered iron preforms in correlation with micro structural parameters. Also impact test and fatigue test were carried out on sintered iron preforms with different sintering parameters such as time and temperature and resulted that the mechanical properties were most sensitive to the sintering intensity. Kang [8] has investigated the suitability of sintered iron-based alloys for severe sliding wear conditions. He has reported that oxidative wear mechanism is found to be predominant on Fe based alloy material due to the formation of solid film oxides of Fe at the relatively higher temperatures between the interface materials. It has been reported that the addition of copper as alloying element to iron based alloys significantly improves the wear resistance of the alloy steels due to predominant delamination wear process. Fodor et al. [9] reported 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. Molinari et al. [10] observed that increase in mechanical properties such as hardness, impact strength along with wear resistance because of the formation of bainitic and martensitic microstructures in the Fe-C-Cr-Mo alloy system. Khorsand et al. [11] noted 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. The wear resistance of high speed steel is enhanced due to the formation of hard carbides by the addition of TiC rather than the addition of MnS and CaF₂. On the other hand the later improves self-lubricating property of the steel [12]. Lorella ceschini et al. [13] studied the wear behavior of sintered steel under both dry sliding and abrasive wear conditions and concluded that the best behavior 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. It has been found by Anton et al. [14] that the addition of 0.7%C to plain carbon steels enhances their wear behaviour as compared to 0.3%C addition, due to the formation of higher volume of pearlite phase in the ferritic microstructure. Philip m. mckenna [15] successfully invented a carbide containing

tungsten and titanium which is extremely hard and highlighted its great value and utility as a material for use, in accordance with the customary principles of powder metallurgy, in the production of hard compositions of matter, in order to attain great hardness combined with great strength, along with a low thermal conductivity and other characteristics. The addition of W to P/M alloys could enhance the wear resistance due to the formation of hard phases in the microstructure. The hardened carbide based P/M alloy steels could be the best choice for replacing the HSS in view of the economics of production [16]. Senthur prabu et al. [17] studied 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 emerging importance of low alloy P/M steels in various applications stated above, and due to their potential high strength and economic structural applications it is important to have a complete understanding of the wear behavior of P/M steels in order to evaluate their suitability for frictional wear applications. The present research is mainly focused on the dry sliding wear behavior of sintered P/M low alloy steels with the addition of Ti as alloying elements with various densities such as 85%, 90 % and 95% under dry conditions on pin-on disc arrangement against EN 38 steel disc of Hardness HRC 60 with a sliding speed of 2 m/s and at a normal load of 30, 50, 70N respectively.

2. Experimental Details

Atomized Iron (Fe) powder of particle size 150 μ m, Graphite(C) powder of particle size 5 μ m, Tungsten (W) powder of 100 μ m and Titanium (Ti) powder of 100 μ m were used for the research work. Elemental powders of Fe, C and W, Ti 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-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**. Using a hydraulic press of 1000 kN capacity, the cylindrical billets of size $\text{\O}25\text{X}33\text{mm}$ has been compacted from the known mass of blended powder to obtain the preforms of 85%, 90%, 95% theoretical density with the help of compressibility chart as shown in **figure 1**. During compaction, graphite was used as lubricant. After the compaction, to avoid surface oxidation aluminium ceramic coating was applied and dried for 24h. In the nitrogen purged inert atmosphere the preforms were sintered by using 3.5kW capacity muffle furnace at $1100 \pm 10^\circ\text{C}$, for a period of 120min to avoid oxidation. Standard wear test specimens of size diameter 6mm were obtained by machining process from the sintered cylindrical billets of size $\text{\O}25\text{X}33\text{mm}$. The actual density of the P/M alloy specimen was measured using Archimedes' principle. Before the specimens subjected to wear test, standard polishing was done using various grit size SiC emery papers and followed by disc polishing so as to get mirror-like polished surface. 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 for carried out dry sliding wear tests on P/M alloy steel pins against counter face EN 38 steel disc (HRC 60). The disc was cleaned in 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 constant sliding speed of 2m/s. The mass loss of the sintered steel pin measured accurately as the change in weight before and after the wear test. Coefficient of friction was also measured during the wear test from the tribometer. The wear mechanism has been systematically characterized by observing the worn out surfaces and wear debris using both optical and scanning electron microscopes.

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-1%Ti	7.66	3.04	3.45	0.51

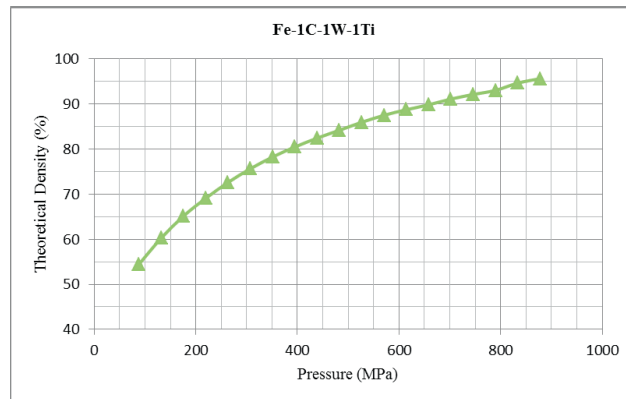


Figure-1 Compressibility chart for Fe-1%C-1%W-1%Ti, Theoretical density V/S Pressure

3. Results and Discussions

The mass losses were expressed as material removal during the test and were recorded as a function of the normal load and sliding distance. The wear of sintered P/M materials is more complicated than that of wrought steels and depends on different factors related to the sintered microstructures of the different phases, as well as the porosity. Basic dry sliding wear curves (wear loss and frictional coefficient versus sliding distance) of titanium alloyed sintered P/M steel (Fe-1%C-1%W-1%Ti) for different densities (85%, 90% and 95%) at constant sliding velocity of 2m/s for an axial load of 30, 50, 70N were obtained.

3.1. Wear Behaviour of sintered Titanium Alloyed P/M Steel

The dry sliding wear behaviour of sintered titanium alloyed P/M steels (Fe-1%C-1%W-1%Ti) is illustrated in figure 2 (a-c).

From the fig. 2(a) it was observed that with low level of applied load of 30N, mass loss of all density preforms increases gradually with sliding distance as per the general principle of wear states that the mass loss increases with increase in applied load, irrespective of speed. Mode of wear under these conditions appears to be mild oxidative. The wear rate rises abruptly above applied load of 50N and that is apparent in 70N also. The important parameters that specify the role of porosity are the amount of porosity and the pore size. Also a dominant role can be played by isolated pores and their shapes. If the amount of porosity lesser than 10 % and a pore size that is smaller than 12 μm constitute a dominant interconnected porosity. These pores are filled with debris particles during wear. This may enhance the wear resistance of the samples by increasing the real contact area and decreasing the contact pressure. The same trend was observed from the plot 2(c) the mass loss is reduced for the higher density (95%) preforms whereas for the 85% and 90% density preforms mass loss increasing linearly with sliding distance particularly in high applied load [1]. The reason may be due to the second phase high dense hard WTiC presence along with porosity (greater than 10%) results in the thermal softening of the material can give rise to considerable stress-concentration effects that favour the nucleation and propagation of micro-cracks, leading to the easier formation of wear fragments [18]. Therefore, delamination wear in the higher load and oxidation wear in lower load seems to be the main wear mechanisms. So the density plays the vital role in the P/M alloy steels to enhance the wear resistance.

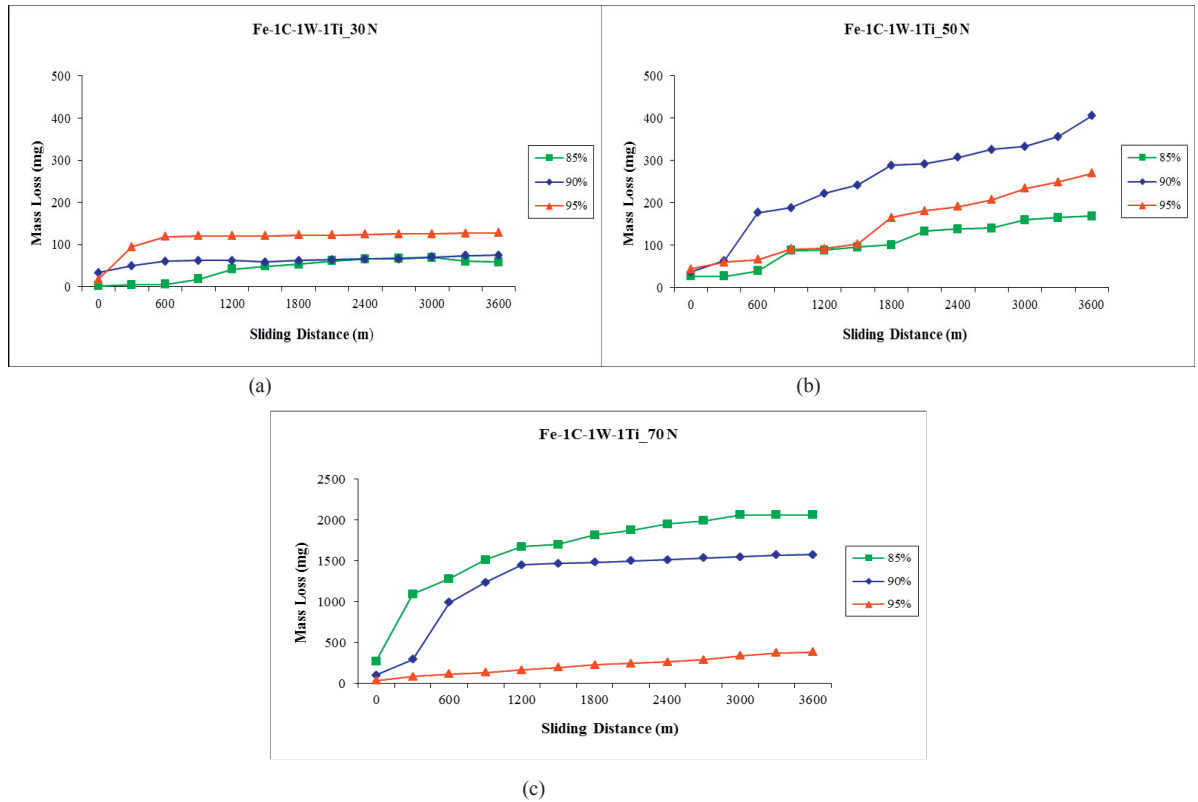


Figure-2 Dry sliding wear behaviour of sintered Titanium alloyed P/M steel (Fe-1%C-1%W-1%Ti) (a) 30N; (b) 50N; (c) 70N

3.2. Effects of Applied Load and Sliding speed on the Frictional Coefficient

Figure-3 illustrates the variations of the frictional coefficient of P/M alloy steels for 3 densities (85, 90 & 95%) at different loads.

The plot 3(a) exhibits that at lower load (30N) initially frictional coefficient at the beginning of the test varies between 0.43 to 0.6 for 85% and 90% density preforms whereas 95% density it was 0.24. The presence of high dense WTiC due to the addition of alloying element embedded along the grain boundaries formed the hard phase contribute to increase in frictional force and intern decrease the wear rate of the alloy steel. For the 90% density preforms the initial lower value of frictional coefficient is due to contact of oxide layers and disc. Breaking and removal of surface oxide layer leading to the metal-to-metal contact causes an increase in the coefficient of friction at higher load. At the higher load (plot 3c) for 95% density preforms the coefficient of friction rises to an average of 0.56 because of increase in interface temperature with incremental in applied load that may promote the surface oxidation and reduce the direct metal contact [19] and thereby decrease in mass loss. The main reason for decreasing trend in wear rate is that these pores are filled with debris particles for porosity lesser than 10 % preforms during wear. This may enhance the wear resistance of the samples by increasing the real contact area and decreasing the contact pressure. Whereas for the lower density (85%) preforms, continuous fracture of discrete oxide film formed at the interface acts as hard impurity or particle (third body) between mating surfaces results in oxidation wear.

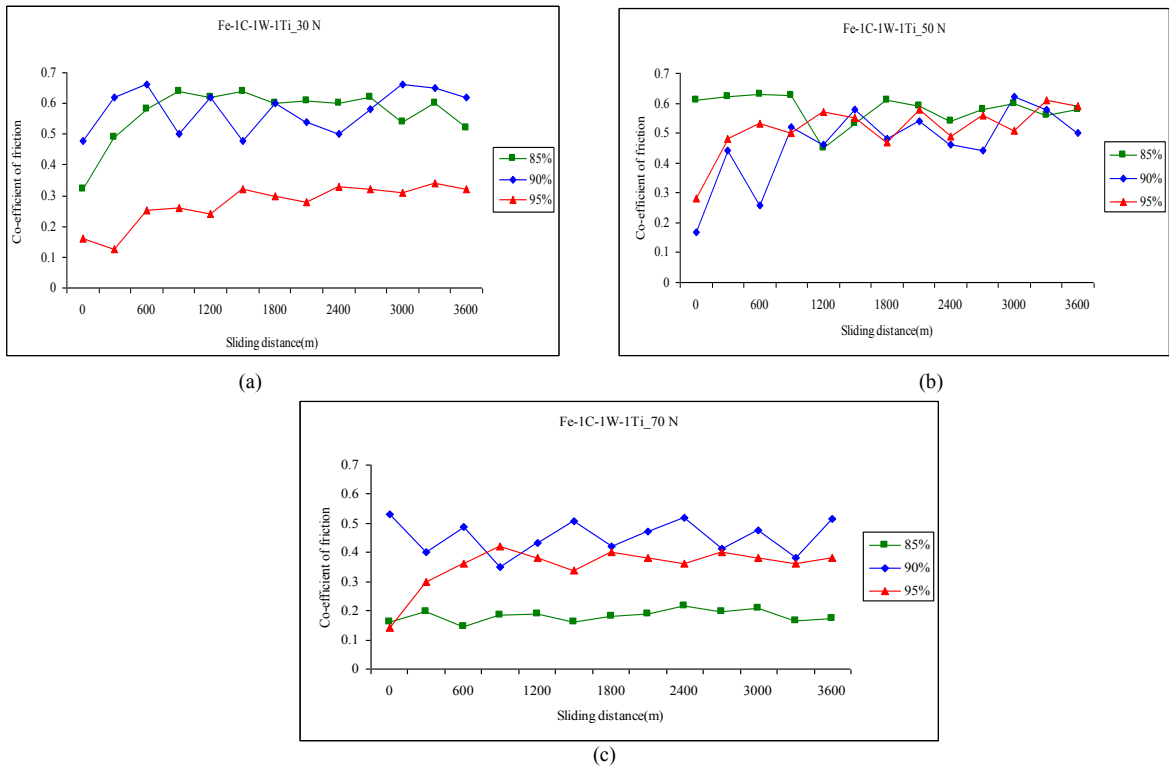


Figure-3 Variation of the frictional coefficient of P/M low alloy steel at different loads (a) 30N; (b) 50N; (c) 70N

3.3. Microstructure of As-Sintered P/M alloy steels

The microstructure of the P/M alloy steels determines their properties. The microstructures of the as-sintered P/M alloy steels used for the wear test are shown in figure 4 (a-c). Basically the alloy steels are containing ferritic-pearlite microstructure and reveals that the uniform distribution of W, Ti particles occupied the ferritic grain boundary areas and strengthen the grain boundary region which enhance the wear resistance of the steels [17]. Titanium and Tungsten is known carbide former. In higher density preforms 95% the WTi carbide phase embedded in between the ferrite grains is bigger in size. Due to the presence of second phase hard WTiC in the material frictional coefficient of P/M alloyed steel is found to be higher.

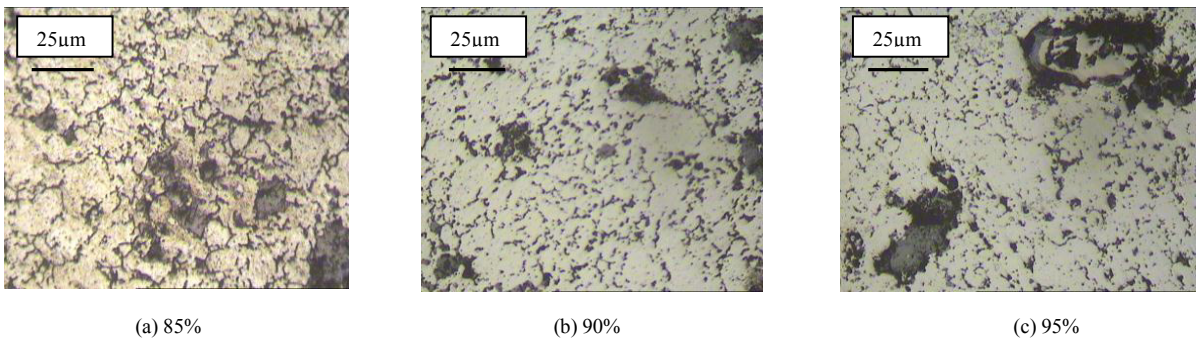


Figure-4 Optical micrographs of the As-sintered Fe-1%C-1%W-1%Ti P/M alloy steels at different densities

3.4. SEM and optical images of the maximum wear surface of the P/M alloy steels

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

Figure 5(a-c) illustrates the morphological observations of wear pattern of maximum worn out surfaces of P/M alloy steels for different densities (85, 90 & 95%) at 70N. Non-uniform wear pattern was observed for low density preforms exhibited from figure 5(a & b) attribute to the presence of second phase high dense hard WTiC because of the addition of alloying element which increases the temperature at the interface between the specimen and the disc material results in thermal softening of the materials. Heat generated at high load causes more oxidation but that is counteracted by continuous fracture causes extent of grooves, craters formed at the worn surface of the preforms indicate metallic wear results in higher mass loss during the wear test [5]. Hard oxide layers due to high temperature are seen to appear as a dark patches in the image. From the figure 5(c) uniform wear pattern was observed for 95% density preforms at high load. Failure by a delamination process is clearly indicated by the shape of the debris particles. The delamination of thin oxide film increases the frictional coefficient at high load but intern reduces the wear loss. The WTiC particle embedded in between the ferritic grains matrix is clear from the SEM micrograph (figure 6a). SEM image of wear debris is shown in the figure 6(b). The wear debris mechanism may include oxidative wear, micro-cutting and delamination flakes because of some oxide particles and also evident from the SEM image.

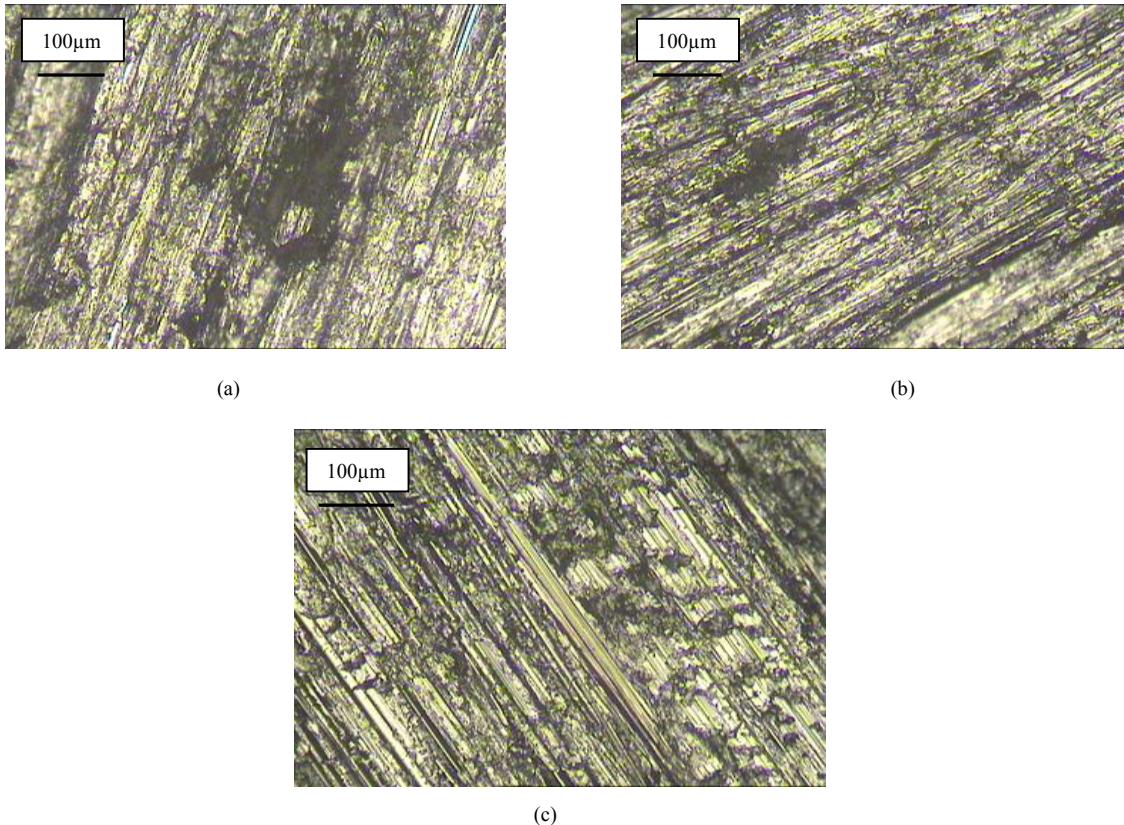


Figure-5 Wear pattern of maximum worn out surface of Fe-1%C-1%W-1%Ti P/M alloy steels @ 70N (a) 85%; (b) 90%; (c) 95%

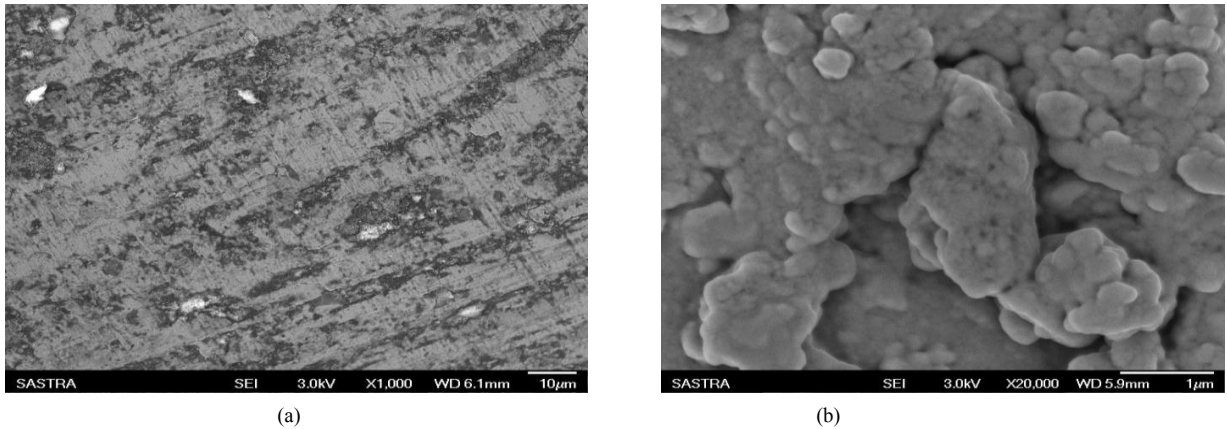


Figure-6 SEM images of Fe-1C-1W-1Ti P/M alloy steels @ 70N (a) Maximum Worn out surface @ 95 %; (b) wear debris @ 95 %

4. Conclusions

From the present study the following points were concluded:

- The wear rate of low density preforms increases gradually with increase in applied load with respect to sliding distance [1].
- At higher applied load mass loss increases abruptly with sliding distance may be due to the second phase high dense hard WTiC in 85% and 90% density preforms results in the thermal softening of the material can give rise propagation of micro-cracks, leading to the easier formation of wear fragments [18].
- The microstructure of Fe-C-W-Ti P/M alloy steel exhibits ferritic-pearlite and reveals that the uniform distribution of W, Ti particles occupied the ferritic grain boundary areas and strengthen the grain boundary region which enhance the wear resistance of the P/M steels.
- At the higher load for 95% density preforms, due to increase in interface temperature with applied load promote the surface oxidation thereby increases the frictional coefficient and reduce the direct metal contact between the disc intern reduces the wear loss [19].
- These pores are filled with debris particles during wear. This may enhance the wear resistance of the samples by increasing the real contact area and decreasing the contact pressure.
- The main wear mechanism in the Ti alloyed P/M steel seems to be delamination wear in the higher load, Failure by a delamination process is clearly indicated by the shape of the debris particles and oxidation wear at lower load. So the density plays the vital role in the P/M alloy steels to enhance the wear resistance.

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