Dry Wear Behavior of 42CrMo4 Steel/ZrO_2 Composite Prepared by Pressure-Less Infiltration Method

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Abstract

The aim of this research was to study the wear behavior of 42CrMo4 steel/ZrO_2 composite with 10 and 30 ppi performed ceramic and compare it with the un-reinforced steel under different applied loads. The composite specimens were obtained by pressureless infiltration of the melt into a preformed ceramic of zirconium oxide. The effect of applied load on the specimens wear behavior was studied by applying the wear test under loads of 90, 120 and 150 (N). The results indicated that at the applied loads, the reinforcement and the increase of volume fraction considerably improved the specimens wear behavior. Furthermore, the microscopic images showed that the increase in force resulted in a change in the wear mechanism of the steel and the 10ppi composite from an abrasive to an adhesive one, while the wear mechanism of the 30 ppi composite remained unchanged as abrasive.

Keywords: Wear; Composite; 42CrMo4 steel/ZrO_2; Pressureless infiltration

1. Introduction

Metal matrix composites are engineering materials with wide thermal and structural applications. They are capable of being used at high temperatures. These materials have high strength, modulus of Young and stiffness. Furthermore, they have good wear resistance, creep resistance and stable dimensions. The purpose of preparing metal matrix composites is to combine the suitable characteristics of the metal and ceramic and also, to decrease the weakness of each part [1, 2)]. In the production of metal matrix composites, the reinforcement distribution and its control are important. Furthermore, the volume fraction and uniform continuity of the reinforcement phase is an effective and important factor determining the mechanical and physical properties of composites [3)].

The use of preformed ceramics as reinforcement phase results in a continuous ceramic and three-dimensional metal structures which can be used to produce metal matrix composites of a homogeneous structure, obtain a suitable bond between the ceramic and the metal, and reach high volume fractions of reinforcement. The use of preformed ceramics to produce metal matrix composites has advantages of: easy production, production of parts with dimensions near the real dimensions, high strength, recovery capability of the ceramic foam production, and the production of composites with a gradual slope of the reinforcement phase [4, 5)].

One of the production methods of metal matrix composites is the pressure-less infiltration, in which the melt enters the porous ceramic foam structure by the capillary force. The advantages of this method are: cheapness, easy control of the reinforcement volume fraction, and the uniform distribution of the reinforcement phase [6)]. Composites with ferrous alloy matrixes are used for parts requiring wear resistance such as different mills and molds. Furthermore, wear resistant MMCs are very interesting for machine parts in pharmaceutical and food industry applications by avoiding contaminations due to higher wear resistance [7)]. Wear resistance of the metal matrix composites has been studied by several researchers, but the comparison between them is impossible. This is due to the reason that the friction and wear resistance are not intrusive properties and change according to such condition such as applied load, atmosphere temperature, slip velocity, type and the volume percent of the reinforce-

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ment. It has been seen that the reinforcement of metals with ceramic material improves the wear behavior of the composite. If the reinforcement has a good bonding with the matrix, the wear rate of the composite is controlled by the reinforcements wear rate, and the increase in the reinforcement's volume fraction causes a decrease in the wear rate of the composite [8)].

Wear resistant alumina/ steel ($Al_2O_3$38CrMoV5-1) MMCs have already been produced by the pressureless infiltration [1, 2)]. The published work first deals with the fabrication and characterization of MMCs based on zirconia ceramic foam structure for improving the mechanical and wear properties due to the higher strength and wear resistance of zirconia, as compared to alumina [9-11)].

The aim of this research was to investigate the feasibility of producing zirconia based MMCs by the pressureless infiltration. Porous preformed zirconia ceramics made of stabilized ZrO_2 (by Y_2O_3) were infiltrated by a steel melt in a pressureless manner. The present work was undertaken in order to evaluate the effect of the reinforcement related parameter (i.e. ppi: pore per inch) and wear conditions on the wear resistance of unreinforced 42CrMo4 steel alloy and 42CrMo4 Steel/ZrO_2 composites. In addition, the wear mechanisms of MMCs based on ZrO_2 were also determined.

2. Experimental Method

2.1. Steel

42CrMo4 steel was used as the matrix to prepare the composite. Table 1 shows the elemental analysis of the 42CrMo4 steel. As can be observed, this steel had a suitable chemical composition.

2.2. Ceramic Preforms

In this research, a zirconia preform of 10 ppi and 30 ppi was used as the reinforcement phase. Due to the difficulties in the preparation of the performed ceramics, they were prepared from market TLS Technik Co., Germany. The performed ceramics were produced by the replica method. For phase characterization, XRD analysis was applied on the zirconia preform. As shown in Fig. 1, the ceramic preform had tetragonal and monoclinic phases.

2.2. Pressure-less infiltration process

The 42CrMo4 steel/ZrO_2 composites were prepared using the pressure-less infiltration process. First, a wooden model was prepared according to Fig. 2. The model was made with the dimensions shown in.

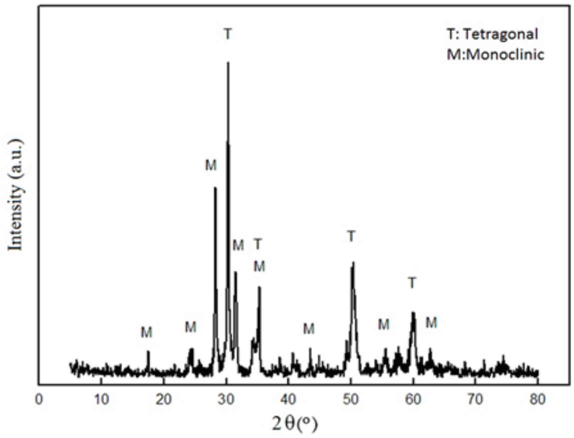

Fig. 1. XRD pattern of the zirconia ceramic preform.

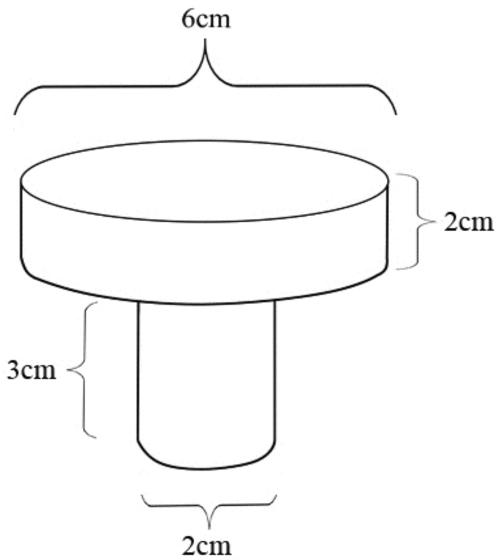

Fig. 2. Dimensions of the wooden model prepared for the molding operation.

As show in Fig. 2, molding was done in a sand mold in order to let the preformed ceramic lie in a suitable place and also, to make the infiltration process occur completely. This was done by considering an empty section at the lower part of the preform to ensure that the ceramic preform was filled by the steel. Then a 42CrMo4 steel billet 5 kilograms by weight was melted at 1600 °C in an induction furnace and directed into the preform through the gateway located at the top of the mold. After the mold was filled with the melt and cooled, the sample was taken out and the excess parts were cut by a lathe machine and the

Table 1. Chemical composition of 42CrMo4 steel (wt. %).

Element Composition	C	Si	Mn	Ni	Cu	Mo	Cr	Fe
wt. %	0.45	0.59	0.81	0.65	0.21	0.11	1.32	95.86

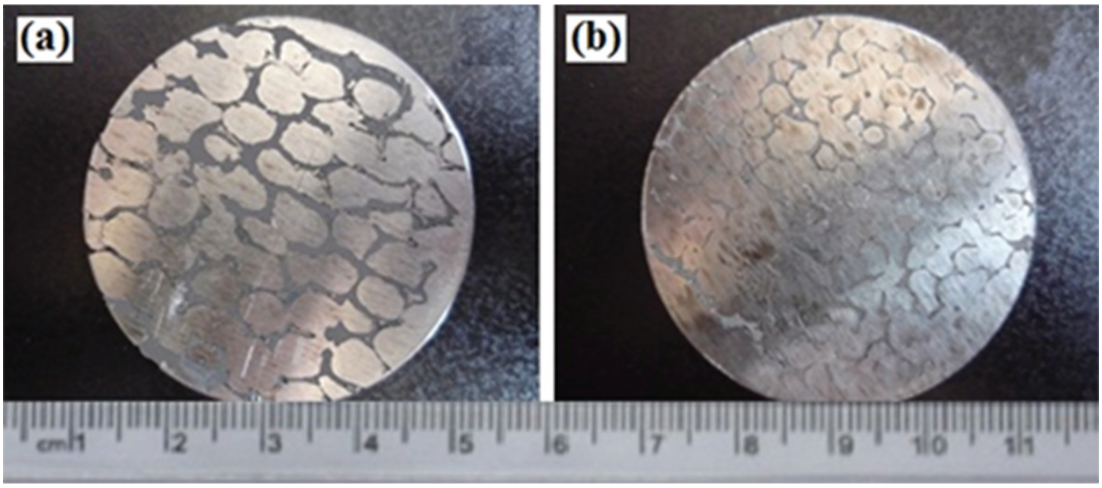

Fig. 3. Macroscopic images of the prepared composites by the pressure-less infiltration: a) 10 and b) 30 ppi.

composite was obtained with a pellet shape of 5cm and the height of 1cm. In order to prepare the specimen without reinforcement, the casting was done without the preform and a disk 5 cm in diameter and 1 cm in height was obtained. Fig. 3 shows the microscopic images of the prepared composites by the pressure-less infiltration.

2.3. Wear test

Wear properties of the composite specimens were studied using dry wear test by a mobile pin-on-disc wear machine, according to ASTM G9995-a. This test was done using disk shaped steel and composite specimens 50 mm in diameter and 10mm in thickness, with an abrasive pin of AISI 52100 steel and 64 RC hardness having the following characteristics: 50 mm height, 5 mm diameter and a contact surface of 3mm, the linear velocity of 0.16 m/s, and the slip distance diameter of 35 mm at room temperature, under dry condition. In order to study the effect of the applied load on the wear behavior, this test was applied under forces of 90, 120 and 150 (N). These selected forces were obtained from the initial tests and the load ability tests. The wear behaviors of the specimens were studied by plotting the curves of friction coefficient and weight decrease versus force. Furthermore, in order to observe and study the wear mechanisms, the surfaces of the samples which had undergone wear were studied using a scanning electron microscope. A wear distance of 1000 m was considered for the test, where the specimens were balanced after distances of 50, 100, 200, 300, 400, 600, 800 and 1000 m.

3. Results and Discussion
3.1. Wear

Fig. 4 shows the plot of friction coefficient versus applied forces of 90, 120 and 150 N. As can be seen, in comparison to the reinforced steel, the unreinforced steel had a higher friction coefficient for all applied loads. This could be explained by the observation that for the unreinforced steel, the wear pin penetrated more in the surface and the periphery of the pin was involved in the specimen, thereby resulting in an increase in the roughness; this, in turn, led to an increase in the friction coefficient. A similar effect was seen by increasing the load from 120 to 150 N. Increasing the load from 90 to 120 N made the surface smother, resulting in a decrease in the friction coefficient. However, with the increase of the load from 120 to 150 N, the friction coefficient was increased due to the further penetration of the pin in the steel matrix. Adding reinforcements to the steel matrix resulted in a decrease in the mean friction coefficient at all applied loads, showing the role of the preform reinforcement. This was due to the reason that the presence of reinforcement increased the hardness of the specimens and therefore, the penetration of the wear pin showed more resistance and prevented an increase in the roughness, resulting in a more uniform wear surface and therefore, reduced friction coefficient. The more coherent presence of reinforcement at the surface and the increase in the involvement between surfaces caused an increase in the friction coefficient of the composites with reinforcements of 30 ppi, as compared to 10 ppi composites. Furthermore, the plots of friction coefficient versus distance for 120 N load in the case of unreinforced and composite specimens are shown in Fig. 5.

Fig. 6 shows the reduced weight of the specimens at different applied loads. It was clearly obvious that with the increase in the normal load during the wear test, the amount of weight reduction and as a result, the amount of the specimens wear were increased. This behavior could be seen for both unreinforced steel and reinforced specimens. This was due to the normal load where the roughness of the surfaces in contact with each other led to the formation of a mechanical lock.

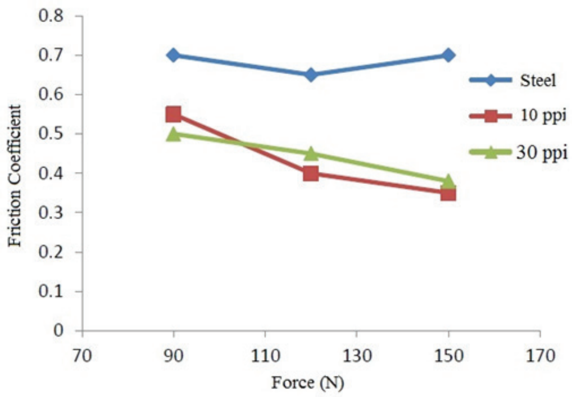

Fig. 4. The plot of the specimens friction coefficient versus force.

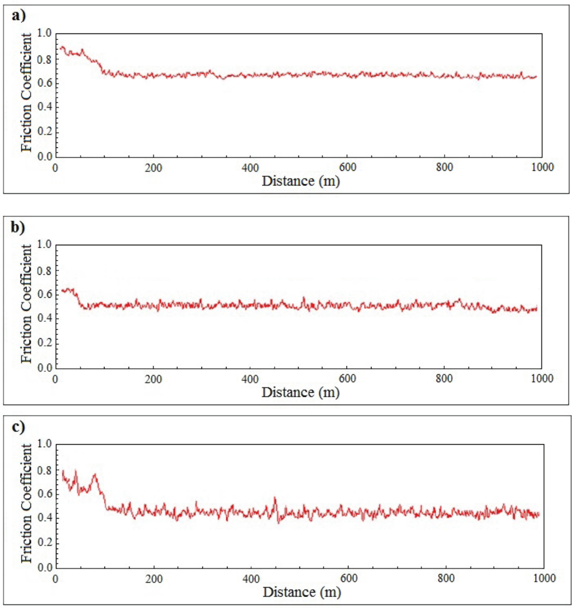

Fig. 5. The plot of the specimens friction coefficient versus distance a) unreinforced steel, b)30 ppi composite, and c) 10 ppi composite specimens at an applied load of 120(N).

Due to the formation of the mechanical lock at the surface, the movement of the surfaces on each other required the wear of the roughness of the surface and hence, the wear of the surfaces. It should be mentioned that at this condition, most of the wear would occur on the surface with less hardness. With the increase in the normal load, the interpenetration of the surfaces in contact with each other was increased and as a result, the relative movement between the two surfaces would led to more wear of the surfaces and further loss. As can be seen, the reduction of the total weight with the increase in the force did not obey a linear trend and the wear behavior of the composites with 30 ppi and 10 ppi reinforcement was different from each other and also, from that of the matrix alloy. As can be seen in Fig. 6, for the composite with 10 ppi reinforcement, the slope of the curve was reduced after the force of 120 N, while for the 30 ppi reinforcement composite, the increase in the slope of the curve occurred. By considering the amount of "reduction weight, according to load" and the interaction of each specimen during wear under different loads, it is obvious that:

Reduction of weight according to load = total weight reduction/ force.

As mentioned, the composite specimens controlled the wear to a large amount and the relative loss of the material for the alloyed specimens was more.

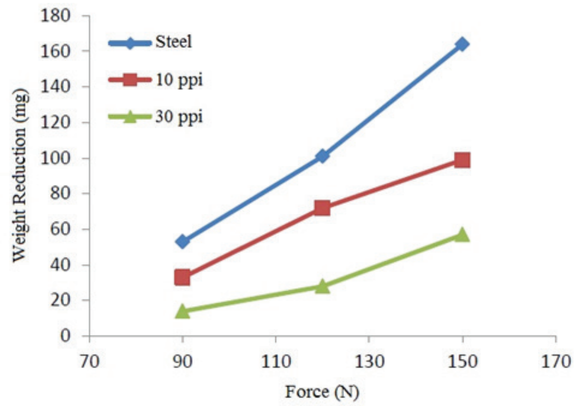

Fig. 6. The plot of weight reduction versus force.

Fig. 7 shows the curve of the total weight loss/ specimens load versus force. It could be seen that at equal applied loads, the un-reinforced steel and 30 ppi composite had the maximum and minimum total weight reduction/ load, respectively. This indicated that the addition of reinforced phase and the increase in its volume fraction caused the reduction in wear amount, thereby confirming the effective role of the reinforcement phase in improving the wear behavior. Also, it could be seen that the composite with 30 ppi reinforcement had a better wear behavior, as compared to the composite with 10 ppi reinforcement.

This could be explained by the difference in the dimension of the reinforcements. Wear is a surface phenomenon and the reinforcements at the surface are under local force; therefore, the size and reinforcement distribution at the surface are very important. For the composite with 10 ppi reinforcement at the surface, the distance between the reinforcements was more than that of 30 ppi reinforcements. The close distance between reinforcements also caused the improved force transfer from the matrix to the reinforcement and the better plastic deformation control of the matrixes.

On the other hand, for the composites with 10 ppi reinforcement at the surface, the steel phase was more than that of the composite with 30 ppi. For this reason, they had more material with less hardness; so it was more prone to wear in comparison with the 30 ppi composite. These reasons show the dominant wear resistance of 30 ppi reinforced composites, as compared to 10 ppi reinforced composites.

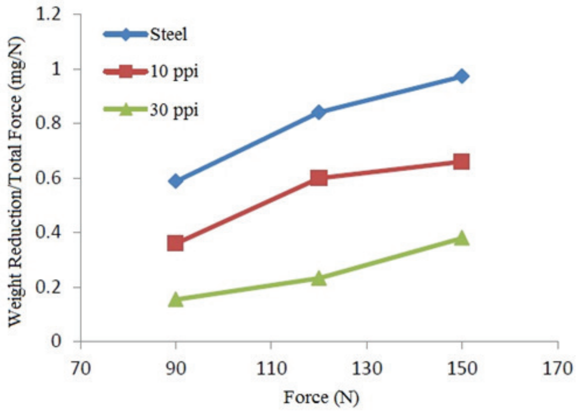

Fig. 7. The plot of weight reduction/total force versus force.

As shown in the plot of Fig. 7, in the study of the effect of the increased applied load on the specimens wear behavior, the wear resistance of all specimens was decreased with the increase of applied load and their total weight reduction/load ratio. Due to the formation of mechanical locks at the surface, the motion of surfaces on each other required the wear of surface roughnesses and further wear of the surfaces. It should be mentioned that at such conditions, more wear would occur at the surfaces with less hardness. With the increase in the normal load, the interpenetration of surfaces in contact with each other would be increased and as a result, the relative motion between the two surfaces could cause further wear of the surfaces and more loss than before [12].

With a closer accurate look at the plot in Fig. 7, it is obvious that with at an increasing force from 120 to 150 Newton, the slope of the total weight loss/ load plot of the 10 ppi composite was decreased while for the 30 ppi composite, it was increased. The reason for such behavior can be due to two factors. The first factor is that the thickness of the cellular preform walls acting as reinforcement is more that in the 10 ppi reinforcement, as compared to the 30 ppi. As a result, for the tolerance of stress, the capability of the 10 ppi reinforcement walls is more than that of the 30 ppi reinforcement walls. The second factor can be the capability of the matrix phase in keeping the reinforcement phase, because with the increase in the applied load, the matrix loses its capability in keeping the reinforcement phase and the reinforcement phase is separated from the matrix; therefore the reinforcement phase is between the wear pin and specimen, acting as an intensifying factor for the amount of wear. As a result, the specimen with more reinforcement will undergo more wear.

3.2. Study on the wear surfaces

Fig. 8 shows the microscopic images of the specimens wear surface at an applied load of 90 Newton. As can be seen, the specimens wear surface underwent slight plastic deformation and the main wear mechanism was an abrasive one. The existence of parallel lines and slight plastic deformation in the images were the main characteristics of the abrasive wear. Furthermore, according to the plot in Fig. 6, it could be observed that the specimens had a small amount of wear, confirming the existence of the abrasive wear. With a closer look at Fig. 8, it could be observed that the unreinforced steel specimen underwent more plastic deformation. It should be noted that although the unreinforced steel had more plastic deformation and disorder, as compared to the composite specimens, its dominant mechanism was the abrasive wear. Fig. 9 shows the microscopic images of the specimens wear surface at the applied load of 150 Newton. With the comparison of this image and the images of Fig. 8, it is obvious that increase in the force from 90 to 150 Newton caused all the specimens to undergo more wear and the plastic deformation; also, surface damages of the specimens were increased. Furthermore, the specimens under wear at 150 Newton, as compared to 90 Newton, had more transverse cracks, which were more obvious for the unreinforced steel and the 10 ppi composite. The studies showed that the increasing trend of the wear with the rise in the applied load could be explained by the formation mechanisms of plastic deformation sections at the layers under the surface in such a way that at small loads, these sections were limited and small and the wear was slight, but with the increase in the load, these sections were extended and the transaction with each other caused the intense wear and change in the wear mechanism. It should be noted that the increase in the load during wear resulted in the increase of the pin penetration in the specimen. If the specimen did not have enough strength, parts of the specimens surface would stick to the pin and pull out of the surface, thereby increasing the amount of wear. Comparison of the microscopic images of the specimens at an applied load of 150 Newton showed that the 10 ppi composite specimen, especially the unreinforced steel, underwent severe plastic deformation, implying the adhesive wear mechanism.

For the 30 ppi composite, it should be mentioned that although it had undergone plastic deformation and transverse cracks were created, due to the dominant existence of notches and parallel lines, the dominant wear mechanism of the 30 ppi composite at an applied load of 150 Newton was still the abrasive wear.

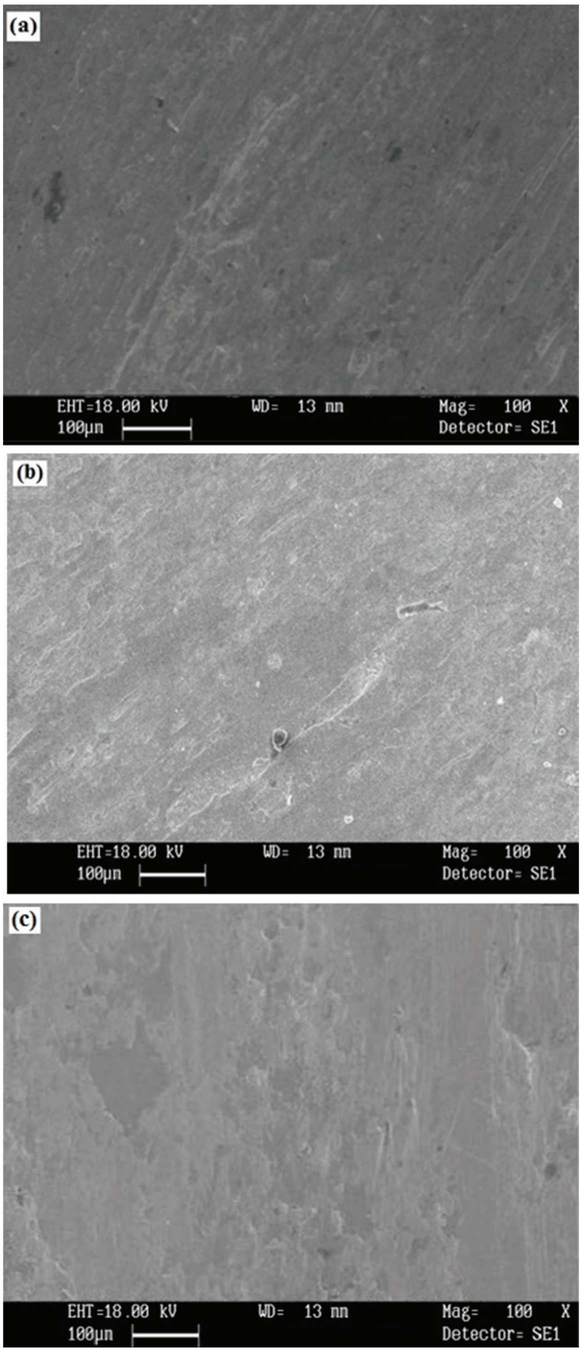

Fig. 8. Microscopic images from the wear surfaces of a) 30 ppi composite, b) 10 ppi composite, and c) unreinforced steel specimens at an applied load of 90 Newton.

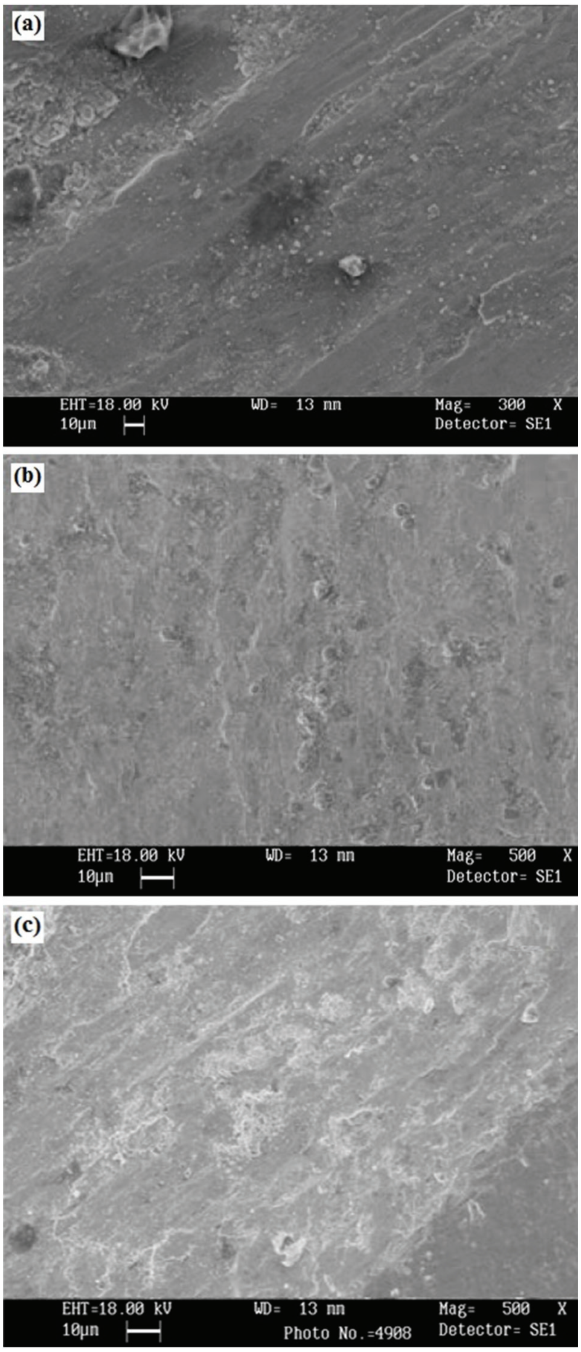

Fig. 9. Microscopic images from the wear surfaces of a) 30 ppi composite, b) 10 ppi composite and c) unreinforced steel specimens at an applied load of 150 Newton.

4. Conclusions

At all applied loads, the amount of the friction coefficient for the unreinforced steel was more than that of the composite samples. With the increase of force, the friction coefficients of the composite specimens were reduced, while they were increased for the unreinforced steel specimens.

At equal applied loads, the unreinforced steel, in comparison with the composite specimens, had a higher amount of wear, indicating that the addition of ZrO_2 foam as reinforcement and also, the increase in volume fraction resulted in the reduced wear rate of the steel. Furthermore, the increase in applied load caused an increase in the amount of wear for all specimens, where the unreinforced steel and 30 ppi composite had the maximum and minimum amount of wear, respectively. At an applied load of 90 Newton, the specimens wear mechanism was abrasive, but with the increase in the force from 90 to 150 Newton, the wear mechanism of the unreinforced steel and 10 ppi composite was changed from an abrasive to an adhesive one, while the dominant wear mechanism of the composite specimen still remained as abrasive.

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