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Investigate the Friction and wear behavior of MoS_2 nanoparticles in solid state lubrication

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Abstract

A solid-state lubricant powders is one of the most significant powders used to protect surfaces from damage in cases of relative motion, with a reduction in the friction and wear between them. In this study, molybdenum disulfide (MoS_2), purity 99%, nanoparticles have been used as solid-state lubrication, due to it having a low coefficient of friction and high wear resistance. In which MoS_2 particles have been distributed with 1.69 x 10^{15} particles per m^2 over the steel disc's surface against the steel pin using a pin on disc tribometer machine. The pin on disc technique was used to study the friction coefficient behaviour of the MoS_2 distribution particles and the position depth of the steel pin on the steel disc surface when the ambient environment was air and humidity. It was used to examine the tribological behaviour of the steel pin on the steel disc surface with no distribution of MoS_2 nanoparticles and also for a steel pin on steel disc with a distribution of MoS_2 nanoparticles. Then, the morphologies and microstructures of the distributions of MoS_2 nanoparticles were characterized using Scanning Electron Microscopy (SEM). In a result, the distribution of MoS_2 nanoparticles have resulted in a lower friction coefficient and higher wear resistance compared with only steel pin on steel disc surfaces.

***Keywords:* Nanoparticles, solid state lubrication, friction, wear, pin on disc machine.**

1. Introduction

Nanoparticles can be defined as particles of scales between 10 and 100 nm. They have significant characteristics and various applications in different fields of medicine, science, and engineering. Then, solid-state lubrication is one of the most important applications of the nanoparticles. Solid lubrication is a type of material used as a powder or thin film to defend surfaces from damage during relative motion, and also to reduce friction and wear. In general, solid-state lubrication is called by other names, such as dry lubrication, solid powder lubrication and dry film lubrication. One of the important factors of using solid lubricant in the lubrication process is that they have low shear strength; they have high wear resistance between the interfacing surfaces in the case of opposing motion [1]. Furthermore, solid lubricants have several advantages, which include a long life, and no contamination for the saving of food in harsh environments in which liquids cannot be applied [2]. In modern technology, solid lubricants are used when other lubricant types (oils and greases) do not provide advanced requirements. Due to the fact they are less expensive than grease and oil lubrication systems for various purposes in applications, and solid lubricants can reduce the weight of the system, for example in aerospace industry, solid lubrication permit to save weight compared with liquid lubricants [1]. Molybdenum disulfide (MoS_2), graphite and tungsten disulfide (WS_2) are some examples of solid lubricants, but the most commonly desirable material is MoS_2 [3].

Molybdenum disulfide (MoS_2) has been used in solid lubrication for several decades; MoS_2 originally came from purification of the mineral Molybdenite [4, 5]. Commercial MoS_2 has a hexagonal layer lattice crystal composition; owing to which it provides low friction and outstanding adherence in most metals [5]. MoS_2, particularly MoS_2 nanoparticles, are the most popular solid-state lubrication material in the engine of instruments which can reduce the wear rate, principally in environmental situations in which oil and grease lubrication are not [6]. Consequently, MoS_2 can be influence on the materials that can be shear more easily in the case of parallel layers than cross each other, due to weak interatomic interactions (van der Waals forces) between their layer constructions [7]. Furthermore, they have capacity to support heavy loads in different environments [8]. As a result, MoS_2 has various applications, such as in aerospace, automotive, engineering, biomedical and food industry applications [1].

The aim and the objective of this study is the use of nanoparticles, particularly MoS_2 nanoparticles, for solid state lubrication. MoS_2 nanoparticles with a purity of approximately 99% have been used to lubricate the steel disc surfaces of a pin on disc machine, this machine is one of the most common techniques used for sliding wear tests in a tribology laboratory. With this machine, the friction coefficient and pin position on the disc surface have been determined for MoS_2 nanoparticles, and the microstructure and morphology have been investigated with run time. In addition, the friction coefficient and pin depth on the steel disc surface with MoS_2 particles distribution have been compared with steel disc without MoS_2 particles distribution.

2. Experimental Work

2.1 Experimental Apparatus

In this study, a tribological laboratory test has been used called the Pin on Disc Machine. With which the characteristics and tribological behaviour of MoS_2 and the substrate can be found, such as the friction coefficient, wear characteristics of the surfaces, pin position on the steel disc surface and lubrication properties. A photograph of the machine can be seen in figure 1, this model is CETR

Figure 1: Photograph of pin on disc machine test. The right side illustrates the enlargement of the steel pin on the steel disc location on the machine.

UMT-2. The principle of this technique is the use of a pin that is fixed and pressed hard on a rotating disc of a defined radius. Furthermore, the laboratory test is directly connected to a computer program, which is helpful to see the running data over the sliding distance.

2.2 Substrate and Pin Materials

For this project a steel disc as the substrate and a steel pin have been used, the dimensions of both the disc and pin are presented in table 1. The shape of the head of the pin is not flat, but it resembles as hemisphere, both pin and disc are shown in figure 2. Before the wear tests, both pins and discs were cleaned by using an ultrasonic bath machine for 10 minute with an acetone liquid to remove any contamination on their surfaces, such as grease, dust and any other contaminants that may be present on the surface.

Name of parameter	Type of parameter	Diameter (mm)	Depth (mm)
Steel disc	------	70	6.8
Steel pin	Pin type A	6.04	12
	Pin type C	6	---
	Pin type E	6	---

Table 1: Substrate materials and pin parameters with diameter and depth in mm

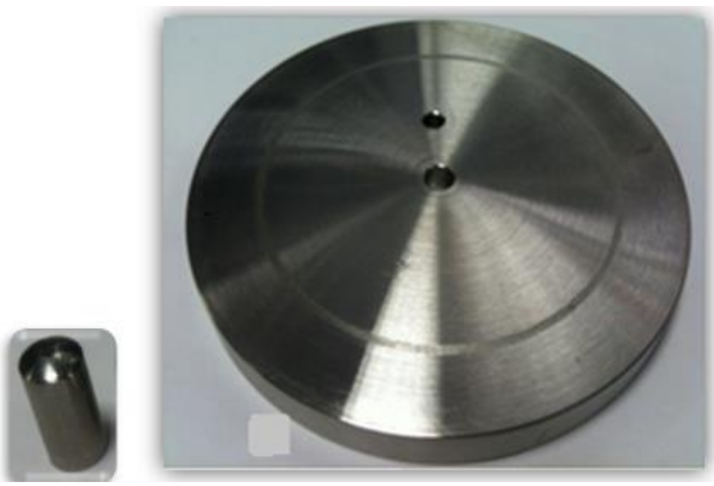


Figure 2: Image of steel pin and steel disc

2.3 Distribution of The Mos$_2$ Particles On Disc Surface

The dry lubricant used in this experiment was MoS_2 powder, and the powders have an average size of 90 nm with a purity of 99.8%. Two samples of steel disc with MoS_2 distributions and without distributions have been prepared. In table 2 the samples and materials used can be seen. The amount of MoS_2 powder used ranged 0.25 g, and these powders were mixed with 20 ml of isopropanol-liquid perfectly. After that, 1 ml mixture of both MoS_2 and isopropanol-liquid were distributed on the surface of the steel discs by hand. The distribution of particles on the surfaces did not perfectly cover the steel surface, in some places the powders agglomerated and in other places the steel surface can be seen. That means that only a small amount of mixture was on the surface, this can be seen in figure 3 which shows the distribution of particles on the steel surface. In general, the number of distributed particles for the sample was 1.69×10^{15} per m^2, if the amount of MoS_2 particles distribution calculated for small area approximately 10 μm^2 on the surfaces, it would be about 1.69×10^5.

Table 2: Prepared samples and their features with and without distribution of particles on

Name of sample	MoS_2 used (g)	Isopropanol-liquid used (ml)	Distribution of particles per m^2	Distribution of particles in 10 μm^2
Steel disc without distribution	------	-------	---------	------
Steel disc with distribution	0.25	20	1.69×10^{15}	1.69×10^5

the steel disc surfaces.

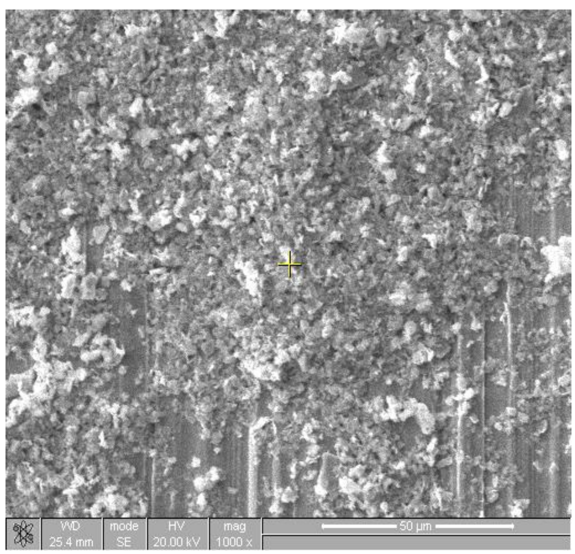


Figure 3: distribution of MoS_2 particles on steel surface sample around (1.69×10^{15} per m^2)

2.4 Test Procedure

After preparation of the samples and the distribution of the particles on the disc surface was completed, the test was undertaken. Various tests have been carried out under different conditions by using the three prepared samples in the pin on disc machine; table 3 explains all the tests and their conditions. The first test was the steel pin on steel disc without any MoS_2 particle distribution interface between them, it was conducted under a temperature of 22 ^{0}C and the humidity was approximately 77%. In addition, several pins have been used which are listed in table 3. The test has been conducted under different times, loads, revolutions and radius of wear track on the surface of the steel discs. The second test was a pin on disc with a distribution of MoS_2 particles on the steel surface (1.69 x 10^{15} per m^2), both first test and second test was run at the same temperature and humidity. However, in the second test only the time was changed and the other parameters of load, revolution, and radius of wear track were fixed.

Name of the test	Pin used	Test condition			
		Time(min)	Load (kg)	Revolution (rpm)	Radius of wear track (mm)
Steel pin on steel disc without MoS_2 distribution on the surface	A	10	0.5	20	25
	C	10	1	60	15
Pin on disc with interface of a low distribution of MoS_2 on the surface (1.69 x 10^{15} per m^2)	A	10	0.5	20	25
	E	30	0.5	20	25

Table 3: Conditions under which tests have been conducted.

2.5 Use of Scanning Electron Microscope (SEM)

SEM is a significant viewing device for the analysis and study of the microstructure of materials. In this study SEM has been used to study the structure and characteristics of the steel pin, steel disc, and for studying the tribological behaviour of the MoS_2 nanoparticles. Then, by using SEM the width of the wear track on the steel disc surface, the size of the wear particles, and the distribution of particles on the steel surface have been determined, and the morphology of the distribution of MoS_2 particles has been investigated.

3. Results and discussion

3.1 Steel pin on steel disc without distribution of mos_2 particles

3.1.1 Friction and wear behavior

The results of the coefficient of friction for this section under various test conditions can be seen in table 4. In the first test when pin A was used with the conditions shown in the table, the coefficient of friction was determined to be approximately 0.75, as shown in figure 4. It is observed that at the time of the start of the test the coefficient of friction of the steel surface has a low value, which is estimated at approximately 0.22, but with the run time this value gradually increased until it stabilized at roughly 0.75. According to Suh and Sin's new theory on friction, they showed that the friction between steel on steel surfaces will rise gradually towards the steady state of the friction coefficient, and then it drops to a constant value [9]. There are some reasons behind this phenomena, one of which is that the first time two surfaces meet each other when the contact area is not very large between them, this is due to the initial surface roughness. As a result, the friction coefficient has a low value, as the contact area between the surfaces increases by removing the peaks of the surfaces the friction value increase. Moreover, according to Wang, Lei and Liu discovery, the dominant wear system would vary from a low rate to a high rate, and this corresponds with the coefficient of friction [10]. These values of friction coefficient for steel on steel materials compared with the results work of Grigoriev, who explained that steel on steel static friction is equal to 0.74 and kinetic friction is approximately 0.57 [11]. Furthermore, Sullivan demonstrated that steel on steel contact materials have 0.7 static friction and 0.6 in the case of kinetic friction [12]. While, in the literature the values are slightly higher than the value in these tests. Due to the fact that these values are not the same for different conditions, such as environment, run time, and temperature.

In case of the second test which is shown in table 4, the coefficient of friction value has a smaller value of approximately 0.44 compared with the first test. The time was the same for the tests, while the other parameters were different such as higher speeds and loads as can be seen in figure 5. The oxidation surface has an effect on the value of the coefficient of friction, for example Ron showed the coefficient of friction for a clean, dry steel surface was 0.78, while if the surface was oxidized the value would be 0.27 [13]. Oxidation can create a thin layer on the surface, and the surface can be protected from contact pressure during the first part of the test. As a result, the friction would be reduced between the two surfaces. Then, with the run time this oxidation and any contamination on the surfaces would clean, resulting in the friction value gradually increasing.

Table 4: Test conditions of pin on disc with no MoS_2 particle distribution on the surface

Sample test name	Pin used	Test no.	Test condition	End point of the coefficient of friction	End point of the height position of the pin (μm)
Steel pin on steel disc without distribution of particle interface between them	A	Test 1	Time: 10 min Load: 0.5 kg Revolution: 20 rpm Radius of wear track: 25 mm	0.75	-18 μm
	C	Test 2	Time: 10 min Load: 1 kg Revolution: 60 rpm Radius of wear track: 15 mm	0.44	-20 μm

(with coefficient of friction and height position of the pin µm)

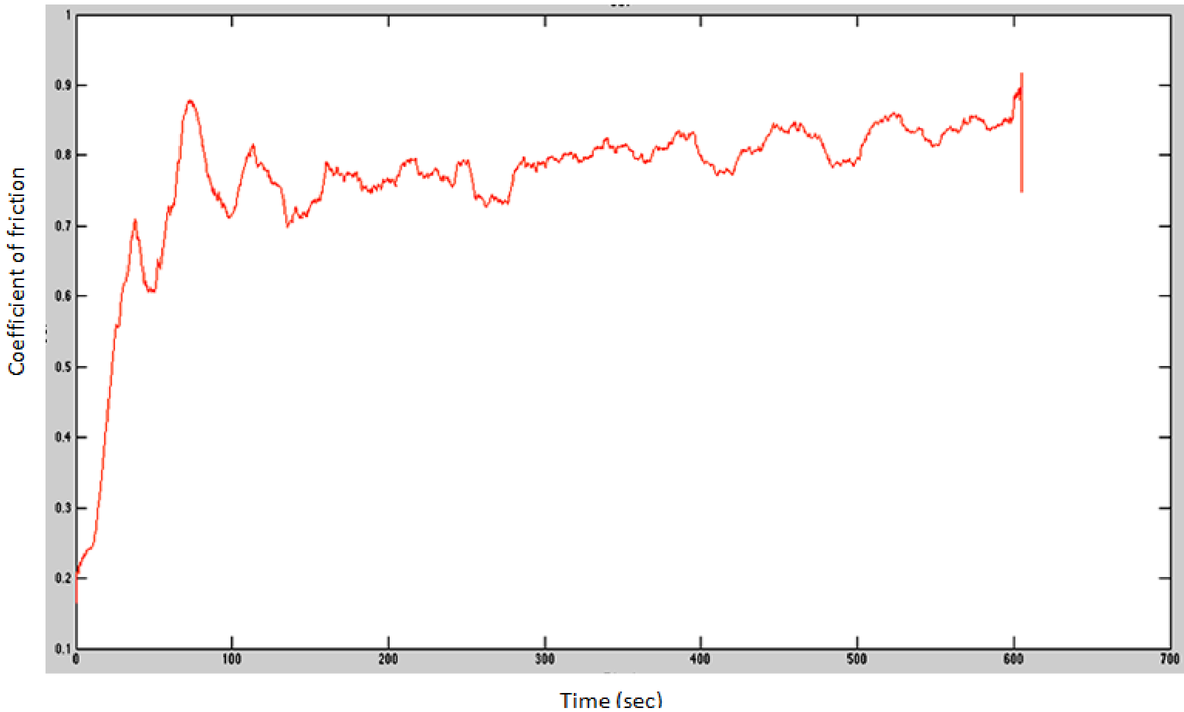


Figure 4: Coefficient of friction with time, with parameters of load (0.5 kg), time (10 min), revolution (20 rpm) and radius of wear track (25 mm)

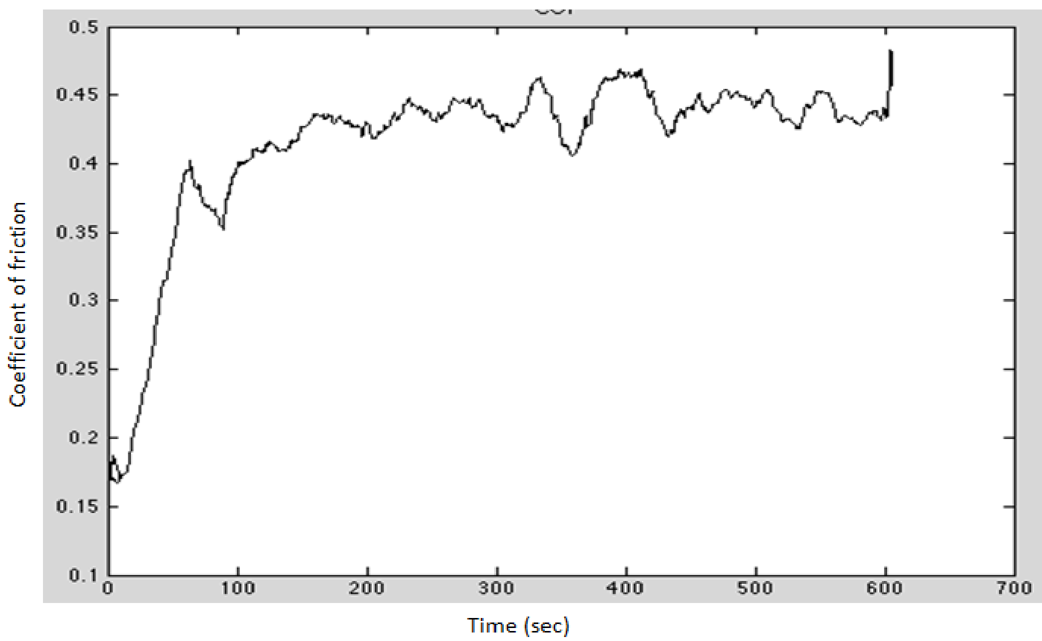


Figure 5: Coefficient of friction with time, with parameters of load (1 kg), time (10 min), revolution (60 rpm) and radius of wear track (25 mm)

3.1.2 Pin positional measurement

The various end points of pin height data resulting from the different test conditions are tabulated in table 4. There are determined by the first and second test which are shown in figures 6 and 7, in which the height of the steel pin on the steel disc surface has been calculated for both tests as approximately -18 µm and -20 µm respectively. According to the figures, it can be noted that the position of the pin on the surface at the start time of the test was slightly raised on the disc surface, while with run time it was gradually reduced down on the steel surface of the disc. Generally, there are reasons behind this phenomenon, for instance surface oxidation, contamination on the surfaces and the environment. Another reason is that when the friction starts to participate interface surfaces, wear particles would be generated between them and then these wear particles remain constant entrapped between the sliding surfaces, within it would be equal to the wear particle interface left between them [14]. In this case, the position of the pin would be above the disc surface.

Within which most surfaces have several valleys and peaks, and at the start of the surfaces meeting the peaks are removed by sliding contact between them, after which the real contact would be occur between them. As a result, the depth of the pin will change from the top layer of the original steel disc to below the disc surface. The sketch in figure 8 shows the position of the pin on the steel disc surface, with the running period the position of the pin changes gradually from being at height to a position below the original steel surface. A positive sign is relative to the increase in height of the pin on the disc; while a negative sign identifies that the pin has gone below the original steel surface. Whereas at the start of the test wear particles would be generated, then with run time the number of wear particles increases in the form of individuals or clusters on the surface. The noticeable factor is that changing the parameters of the tests did not greatly affect the behavior of the position of the pin on the disc surface; while the time was the effectiveness parameters in this study on changing data. Moreover, several researchers have studied wear behavior for different materials and found that wear behavior is the same for all of them, which is an increase from low to high values during running time [15]. Additionally, oxidation is one of the significant characteristics to reduce wear on the surface, particularly when the process has been conducted in the atmosphere. Owing to which the oxidation layer would be generated from an interaction with water and oxygen on the top of the surface, and it protects the surface from friction and wears [16].

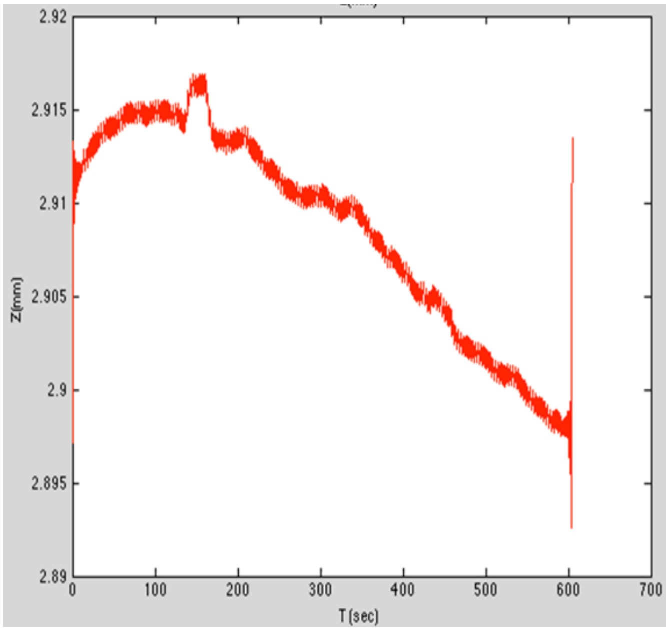


Figure 6: Height position of pin on disc (Z mm) with time (sec), under conditions of time (10 min), revolution (20 rpm), load (0.5 kg), and wear track radius (25 mm)

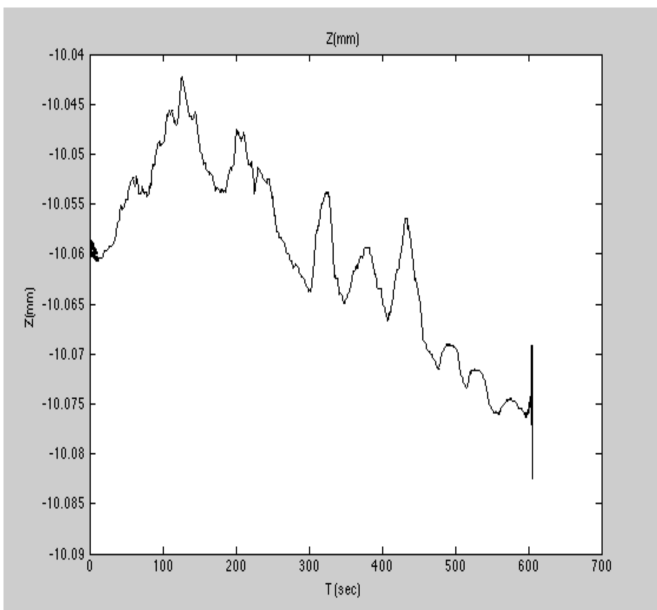


Figure 7: Height position of pin on disc with time under conditions of time (10 min), revolution (60 rpm), load (1 kg), radius of wear track (15 mm)

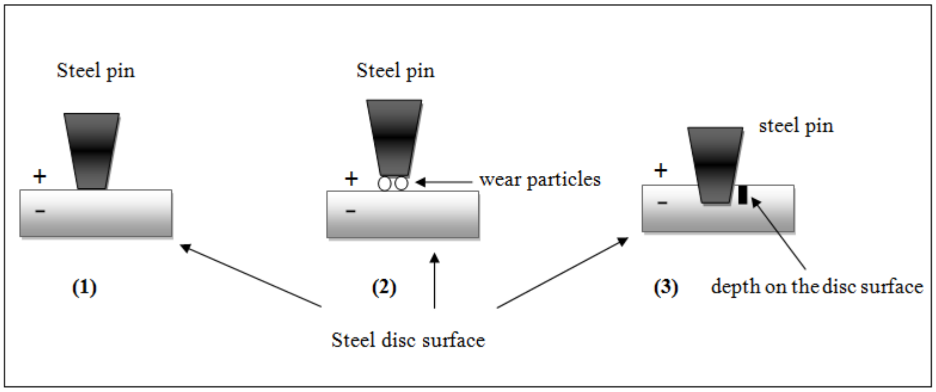


Figure 8: Diagram of pin position on the steel disc surface: 1) time of pin touching the disc surface, 2) when the wear particles are generated between both surfaces, 3) when the pin moves below the original disc surface

3.1.3 Morphology and Microstructure

Figure 9-a offers an overview of the scanning electron microscope (SEM) images of the worn surfaces of the steel surfaces under test 1 conditions, which are tabulated in table 4. In the figures, the scratch surface can be seen in the form of white powder and is separated on the steel disc surface, within which tiny particles can be noticed that are thrown away from the contact surface. The wear track width on the steel surface is measured in Image J software program, was and is approximately 0.92 mm. Enlargement figures demonstrate the wear particles on the surface, in figure 9- b the outside of the wear track shows that the surface has a smooth layer without any scratches on it. In the enlargement image of figure 9-c, the particles can be seen that have been thrown away from the contact surfaces by pressure of the pin on the disc, and they agglomerate in the form of group particles with some tiny separate particles on the surface. Within which the shape of the wear particles is amorphous.

On the surface of the steel disc, two lines are observed on both sides of the center of the wear track, this is due to the pin shape, which is hemispheric. Then, only the peak of the pin is in contact with the disc surface. Figure 9-d shows a smooth surface with fewer scratches, due to space between the pin curve and flat disc, and the scale of the particles scratched on the surface was measured at around 28 µm. In addition, the center of the wear track is shown in figure 9-e, where the wear particles and scratch surface can be seen. The size and the shape of the worn particles are different; in some places they are agglomerated as a matrix group of particles with a size of approximately 42 µm, besides which single small steel particles are evident on the surface of around 10 µm. Even though, small worn particles can be seen on the surface. Due to both surfaces are rubbing on each other according to relative motion. While with running time this layer would be broken into various size particles as small particles, large particles and even clusters. Additionally, both A and C steel pins had been scratched due to contact between the surfaces with run time. Both pin-scratched surfaces are shown in figure 10. On the surface of the pin A, worn surface particles are observed in the form of white powder which is thrown away from the center of the wear track, these worn particles either came from the disc's steel surface or are generated from the steel pin's own surface. However, in the case of pin C, the surface is scratched less than pin A, and compared with pin A on the outside of the wear track wear particles are not greatly observed.

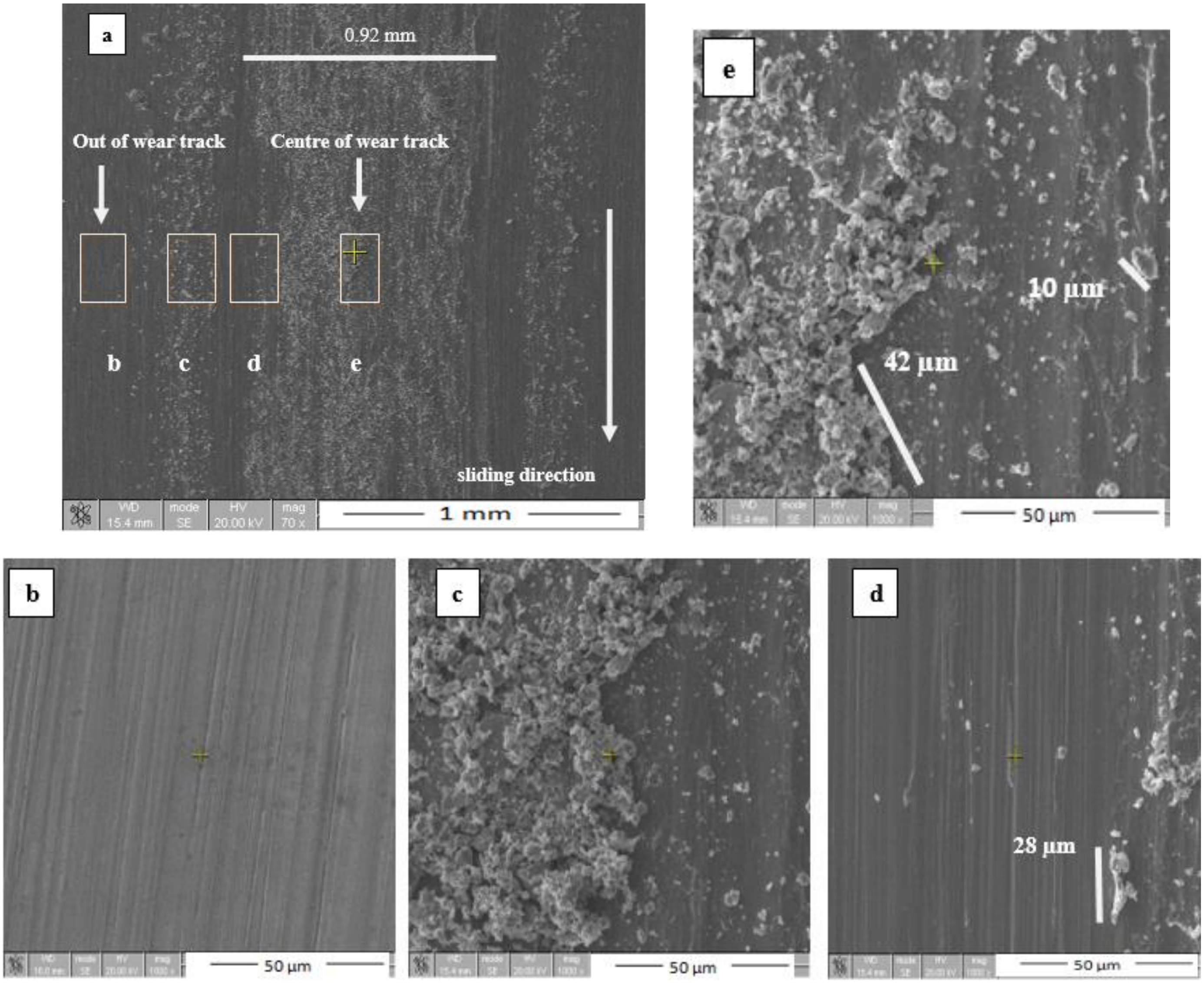


Figure 9: a) SEM image showing an overview of the worn surface of steel disc: normal load (0.5 kg), time (10 min), revolution (20 rpm) and radius of wear track (25 mm) at 70 X; b), c), d) and e) show the enlargements of the worn surface at 1000 X

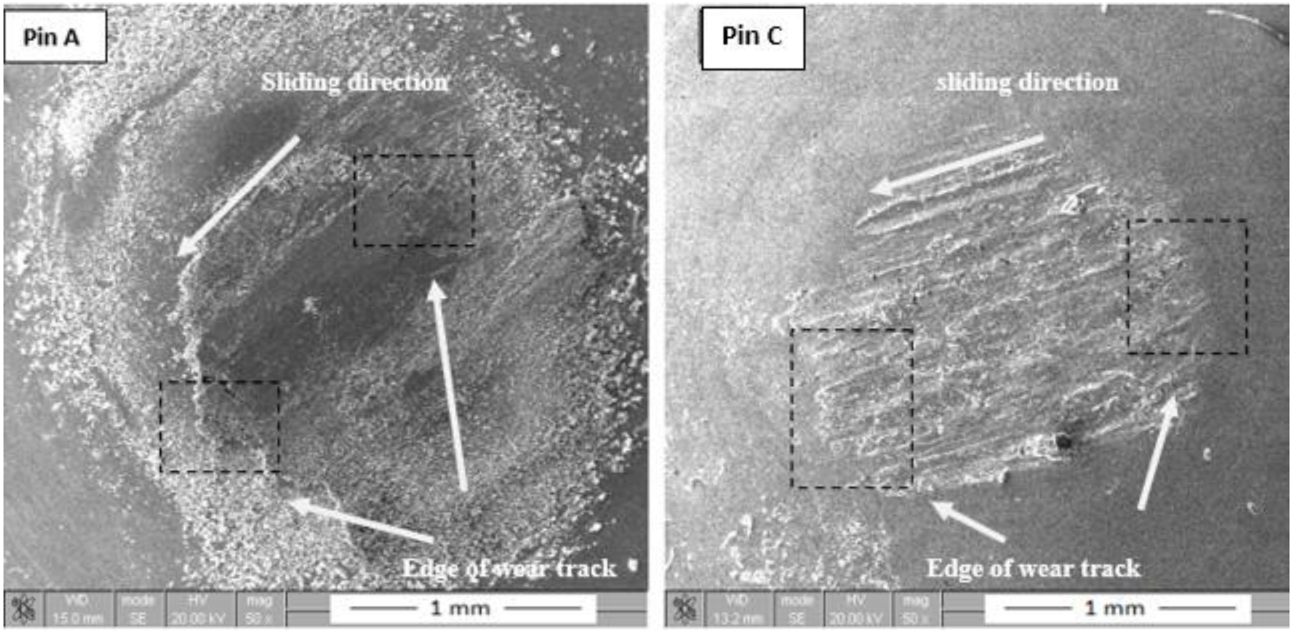


Figure 10: Worn surface for pins A and C, at magnifications of around 50 X

3.2 Steel Disc On Steel Pin with Interface Distribution of MoS_2 Particles (1.69×10^{15} per m^2)

3.2.1 Friction and Wear Behavior

The results of the coefficient of friction for this section with different test conditions have been tabulated in table 5. In this section, the MoS_2 nanoparticles have been used as a lubricant between the surfaces of the steel pin and steel disc, and the distribution of particles on the surface is approximately 1.69×10^{15} per m^2. In test 1, the coefficient of friction (under test conditions of time 10 min, load 0.5 kg, revolution 20 rpm and radius of wear track 25 mm) have been carried out, and in figure 11 the coefficients of friction for this test has been shown. From this figure, the value of the coefficient of friction at the time of first contact between the two surfaces has been determined as approximately 0.2, and with run time this value has fluctuated until reaching the highest value at a time of approximately 380 sec when the coefficient of friction was more than 0.55. Then this value rapidly decreases, and it is slightly fixed at around 0.25. In general, it can be estimated that the coefficient of friction is typically around 0.25 for all of test 1. If these values are compared with those of the previous section (section 1, steel pin on steel disc) it can be noticed that the coefficient of friction of this test has a low value. In the case of steel on steel without distribution particles it was 0.75, while the distribution of the MoS_2 used in this test gave a value of 0.25. Consequently, the MoS_2 powder plays a significant role in reducing friction between the two surfaces. Donnet et al. showed that the coefficient of friction of MoS_2 in dry air would be around 0.150 [17]. According to the results of Holmberg, he determined that for single crystals of MoS_2 the coefficient of friction was approximately 0.05 to 0.1 in a vacuum [14]. In addition, he mentioned that the value of the coefficient of friction of MoS_2 was around 0.1 to 0.2 in air and water under conditions of slow sliding with 0.5 N loads [14].

The coefficient of friction of MoS_2 depends on several parameters, such as a dry environment, moist environment, temperature, sliding speed and normal load. In this section, and particularly in test 2, the run time was approximately 30 min and the value of the coefficient of friction increased drastically, which is shown in figure 12. Figure 12 illustrates the coefficient of friction changing with run time, the coefficient of friction value fluctuated from a starting point until 10 min into the test. It can be estimated that the coefficient of friction is around 0.2, while after that this value increased rapidly to approximately 0.45. Reference [14] explains the phenomena of the changing behavior of MoS_2 as a lubricant, when coating it on steel surfaces. This has been presented in figure 13. He explained that at the start of the sliding test the MoS_2 hexagonal structure became the layer between the surfaces parallel to the sliding direction, called a running period [14]. Then, when the sliding disc rotated with run time for some cycles the crystal structure breaks down, and the steady state start which is represented by the lowest coefficient of friction and the lowest wear particle rate in this condition. After that, the failure time typically starts which includes the scratch surface and the generation of wear particles on the surface, and the mild wear changing to severe wear during the process. Owing to which the friction also increases rapidly to a high value, which occurred in the second test. Within this behavior, the position of the pin is pressed down by the passing normal load. Consequently, the MoS_2 particles distribution for surfaces can reduce the friction coefficient for a limited time during the lubrication process, after which it can no longer protect the surfaces of the metals from friction and wear.

Table 5: Test results of steel pin on steel disc with interface distribution of MoS_2 particles of approximately 1.69 x 10^{15} per m^2. Results shows the coefficient of friction and the change in

Name of the test	Pin used	Test no.	Test condition	End point of the coefficient of friction	End point of the position of the pin (μm)
Pin on disc with interface distribution of MoS_2 particles of about 1.69 x 10^{15} per m^2	A	Test 1	Time: 10 min Load: 0.5 kg Revolution: 20 rpm Radius of wear track: 25 mm	0.25	-10 μm
	E	Test 2	Time: 30 min Load: 0.5 kg Revolution: 20 rpm Radius of wear track: 25 mm	0.45	-15 μm

position of the pin on the disc (μm) with time (sec)

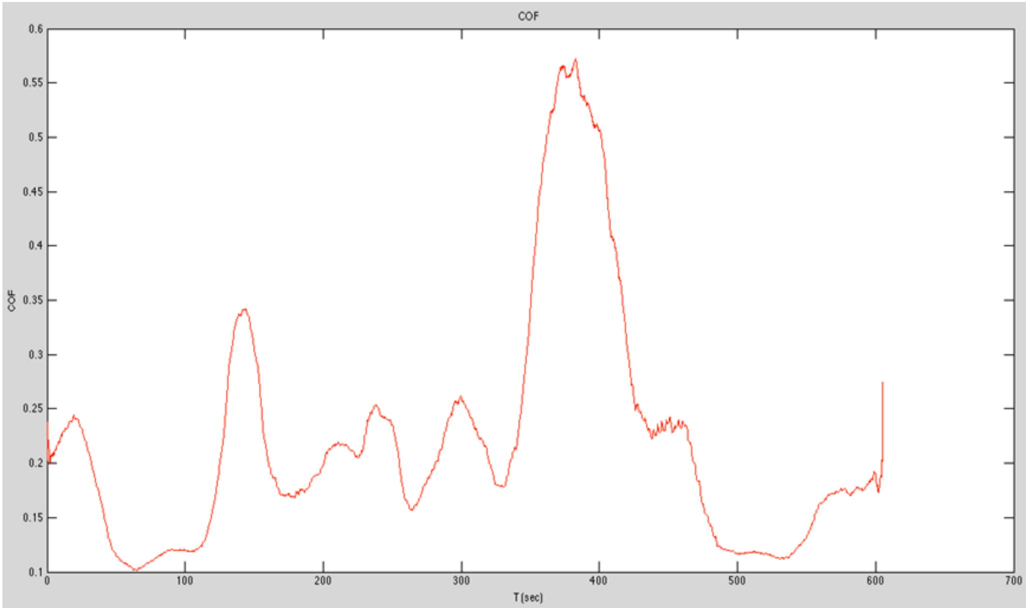


Figure 11: Coefficient of friction changing with time for test 1 in the case of a low distribution of MoS_2 particles (1.69 x 10^{15} per m^2) on the interface between the steel pin and steel disc surface.

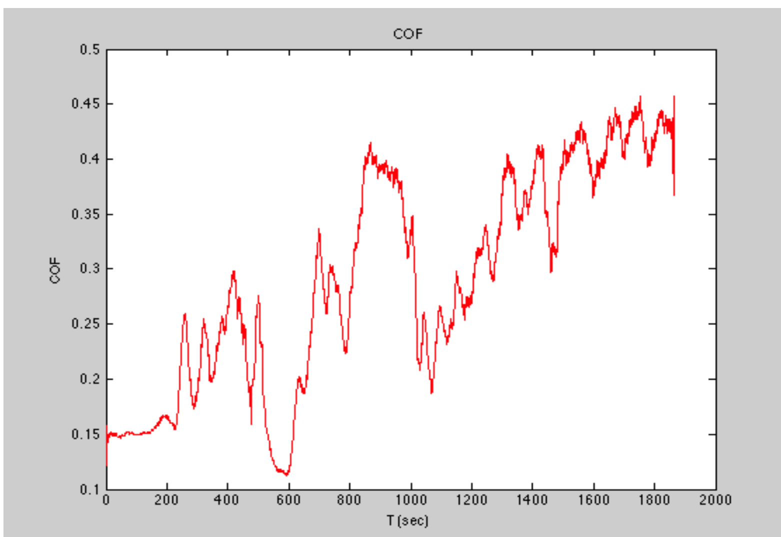


Figure 12: Change in coefficient of friction with run time for steel pin on steel disc with a low distribution of MoS_2 particles (1.69 x 10^{15} per m^2)

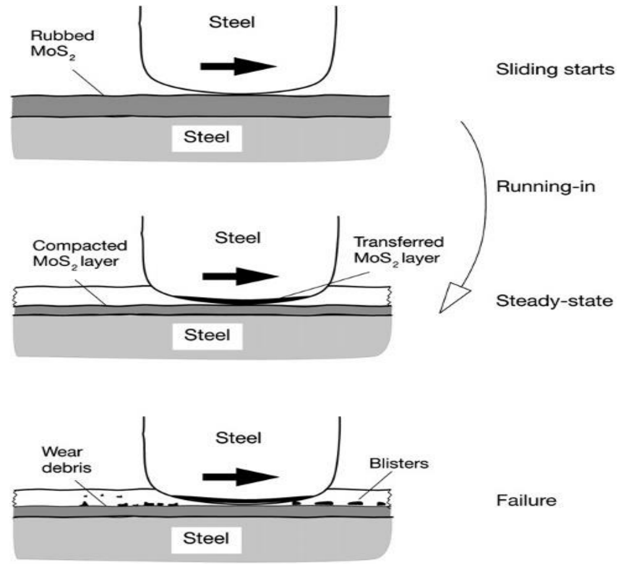


Figure 13: Three process properties (running in, steady state and failure) of MoS_2 in the lubrication process interface between steel pin and steel disc.

3.2.2 Pin positional measurement

The results of the height of the pin have been presented in table 5; in test 1 the height of the steel pin on the steel disc surface has been shown in figure 14. According to the figure, the height of the pin reduces gradually into the disc surface, and the whole pin depth created on the steel disc surface is approximately -10 µm. If this value is compared with the value of the pin position on the disc in section one (steel pin on steel disc without lubricant particles), the depth is smaller. Due to the lubricant particles of MoS_2 having been used in this section between the two steel pins and steel disc surfaces. As a result, the contact area would be smaller between the two surfaces, and the depth on the original disc surface would be small. Owing to this, the wear particles would also be fewer than in the previous section. However, this position of the pin would still not be small, with run time the distribution of the MoS_2 particles on the surface are removed by normal load between the two surfaces. Owing to friction increasing gradually, the scratch surface would then occur. Then, small wear particles are produced on the surfaces, and after that the depth would be generated with run time. In this section, particularly in test 2, the wear test had been carried out for a longer time than test 1. The height of the pin in this test has increased by approximately -15 µm, which is shown in figure 15. While, if this value of pin depth on the surface is compared with test of the steel pin on the steel disc without lubrication particles, the value is smaller. That means the MoS_2 distribution particles could protect the surface for a limited time, and could also reduce the wear depth on the surfaces for a restricted period.

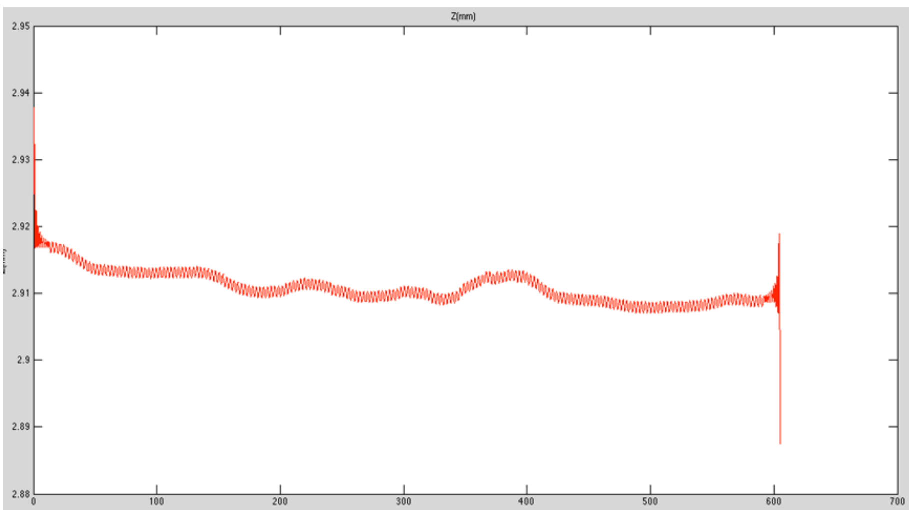


Figure 14: Height location of pin on the steel disc (mm) with time (sec) under conditions of time (10 min), normal load (0.5 kg), revolution (20 rpm) and radius of wear track (25 mm).

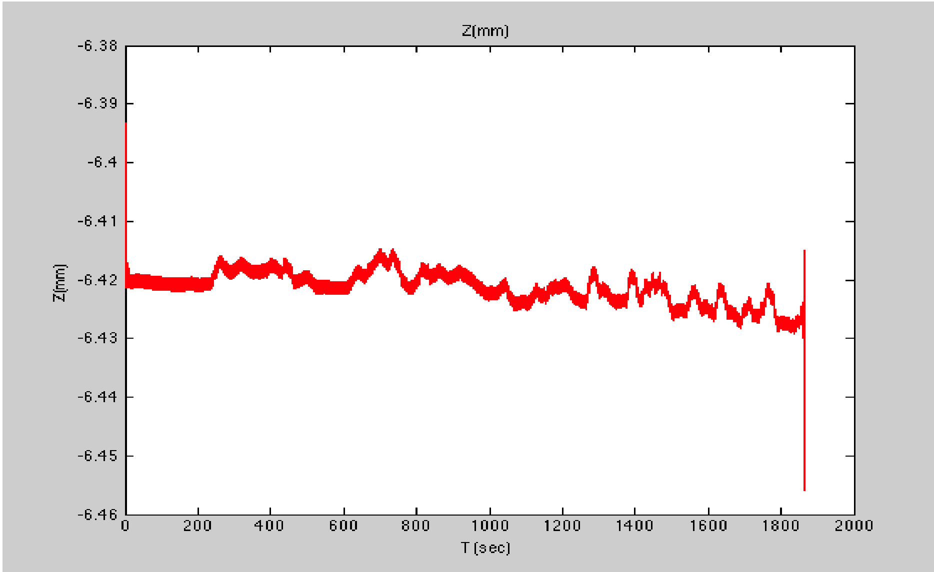


Figure 15: Height location of pin on the steel disc (mm) with time (sec) under conditions of time (30 min), normal load (0.5 kg), revolution (20 rpm) and wear track on the surface (25 mm)

3.2.3 Morphology and microstructure

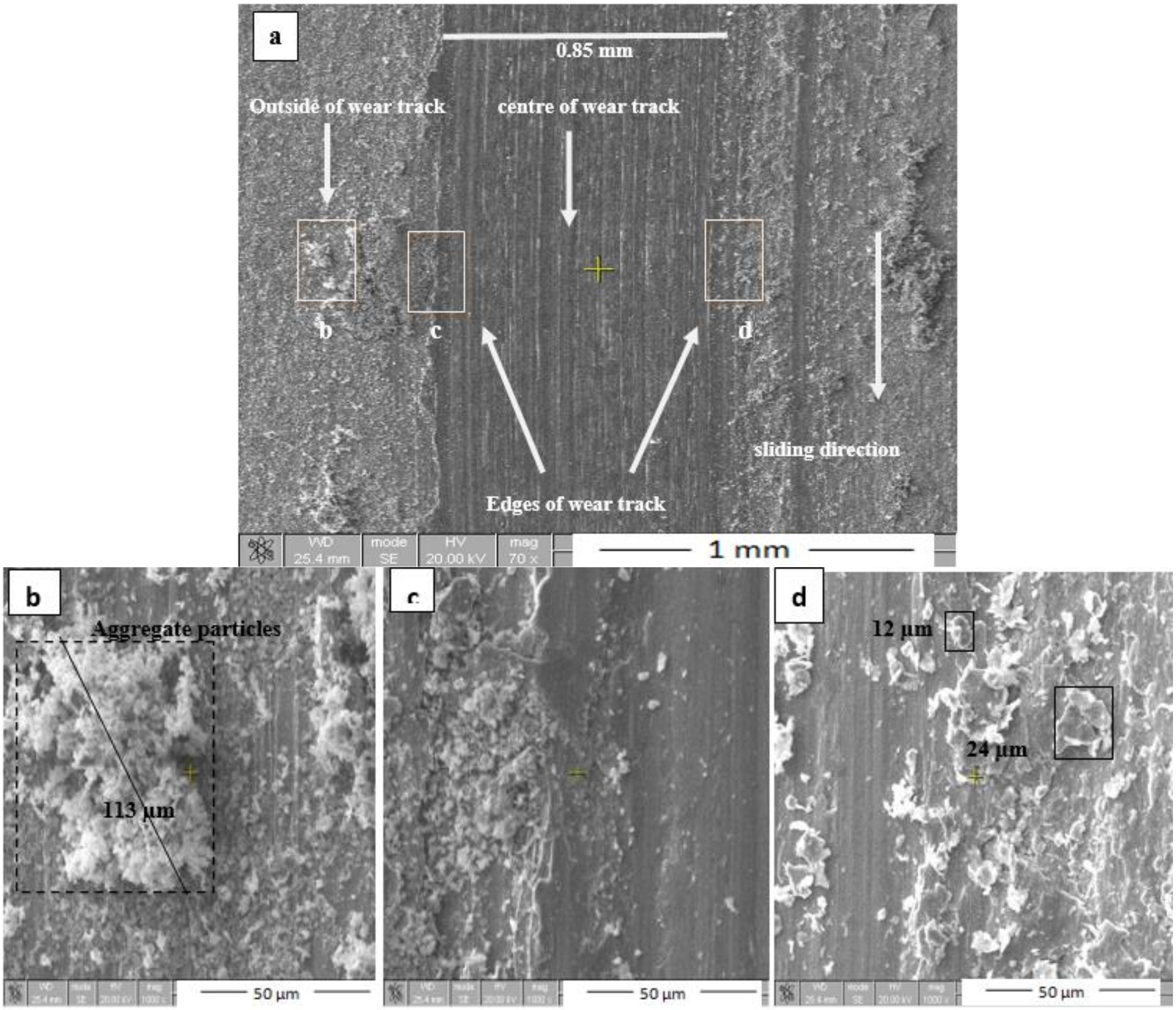
Figure 16-a shows the overview SEM images of the test steel pin on the steel disc with a distribution of MoS_2 particles of approximately 1.69 x 10^{15} per m^2 on the interface between them, and it has been done under test 1 conditions as shown in table 5. The wear track on the steel surface can be seen clearly with a width of approximately 0.85 mm; while the wear track is observed to be smoother than in the test without distribution particles on the steel surface. Then, the enlarged figures illustrate the worn surface of the steel and MoS_2 particles on the surface. In figure 16-b, the debris wear in the form of group-agglomerated particles can be observed, which occur during sliding wear, and they are thrown away from the wear track. Within which the size of the cluster particles was measured at approximately 113 µm. These group particles would be either steel or MoS_2 particles on the surface. At the edge of the wear track the MoS_2 particles can be

seen to form one layer on the steel surface, however it remains to be pressed between the two surfaces as can be seen in figure 16-c. While in the case of steel on steel without distribution no layer to protect the original disc surface could be observed.

In the situation with the distribution, the debris wear particles are not small and they are agglomerated. Hu explains that agglomeration is a common characteristic of nanoparticles, since due to van der Waals forces they can be held together [18]. The shape of the debris particles is amorphous; due to the normal load between the surfaces that has broken the hexagonal structure of the MoS_2 particles. In the centre of the wear track, the depth on the disc surface can be clearly identified between the two lines, while the distribution particles have generated a soft layer on the surface to protect the surface from friction and wear. On the other side of the edge of the wear track, some particles would still be observed impressed into the surface, and they are spread over the surface in different shapes. Sahoo showed that during sliding the MoS_2 particles were removed by basal slip, and then debris particles would be generated, some of them remaining on the wear track and some of them leaving the wear track [19]. With agglomeration, the small wear particles and MoS_2 particles can be seen in figure 16- d, with sizes of around 12 and 24 µm.

In addition, in test 2, which conditions are presented in table 5, the time is longer than in test 1 and by using SEM, the wear particles can be seen on the surface. Near the center of the wear track many small particles can be observed spread on the surface, as shown in figure 17-a. Within which, near the edge of the wear track the large agglomeration of worn particles can be observed, shown in figure 17-b. Due to the fact that with run time the sliding scratched the surface, and then collected worn particles together in the form of a group of agglomerated particles. In addition, pin E has been used in these testes, and by using SEM the scratch surface can be seen in figure 18. At the surface of pin E the depth can be clearly seen, while in the case of pin A shown in the previous section, the pressed layer with many tiny particles can be identified.

Figure 16: a) SEM image showing overview of worn surface of the steel disc, when it was



distributed MoS_2 particles approximately (1.69×10^{15} per m^2) at 70 X; b), c) and d) illustrate enlargements of the worn surface at 1000 X.

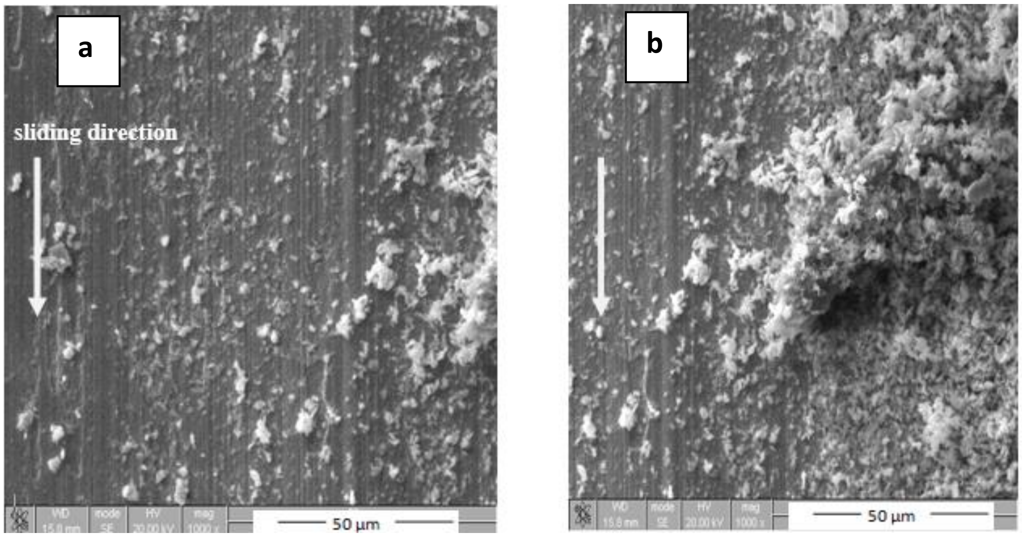
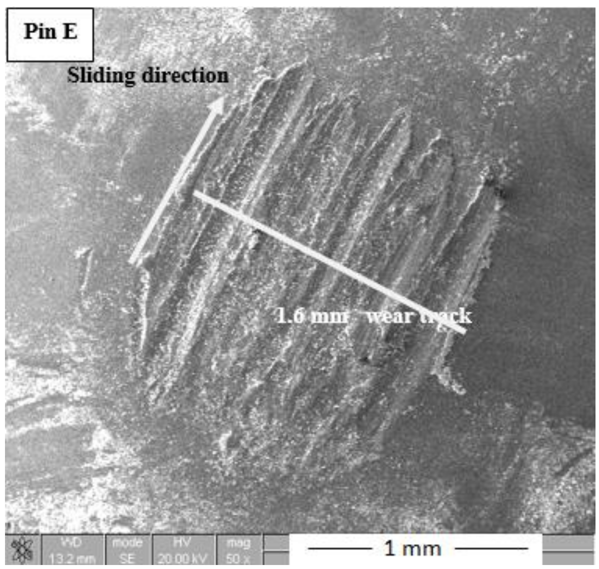


Figure 17: SEM image showing the worn surface of the steel disc with MoS2 distribution



particles for test 2 tabulated in table 5: a) near the center of wear track, b) showing the edge of the wear track

Figure 18: SEM images of worn surface of pin E

4. CONCLUSION

A significant effect of using MoS_2 nanoparticles as a solid- state lubricant has been demonstrated, by using a pin on disc tribometer machine. The distribution of MoS_2 nanoparticles between two steel surfaces have resulted in a lower friction coefficient and higher wear resistance compared with only steel pin on steel disc surfaces. When a distribution of MoS_2 nanoparticles (1.69×10^{15} per m^2) was tested, the coefficient of friction result showed the amount of 0.25 and 0.45, and the pin depth on the steel surface resulted approximately – 10 µm and -15 µm respectively for the tests. However, for the surfaces without lubrication, coefficient of friction resulted 0.75 and depth of pin on the surfaces calculated approximately about -18 µm and -20 µm. As a result, MoS_2 nanoparticle lubricant demonstrated better tribological behavior, meaning a lower friction coefficient and longer protection of surfaces from wear and damage.

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