WEAR OF METAL MATRIX COMPOSITES

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ABSTRACT

The objective of the present work is to investigate the wear patterns of two aluminum-base composites reinforced with Al_2O_3 and SiC particles of varying volume fraction during dry sliding conditions. A pin on disc apparatus was used to perform the experimental work. The pin material was manufactured from aluminum alloys reinforced by Al_2O_3 and SiC particles. The disc was manufactured from high carbon steel. The experimental work was coducted for different sliding distances, operating pressure and temperatures. The obtained results indicate that, the wear pattern depends on the level of operating pressure. At low operating pressure, abrasion wear was observed during running-in period, oxidation wear prevailed in steady state wear period, at higher operating pressure. These different patterns of wear were investigated by the analyses of the worn surfaces and the collected debris using scanning electronic microscope and X-Ray analyzer. The obtained results revealed also that, the wear rate increases with the increase of volume fraction and hardness of reinforcing particles in the abrasive and adhesive regimes. The wear changes from mild to severe wear at a transition pressure, this pressure increases as the volume fraction of particles increases. The composite material reinforced with Al_2O_3 particles experienced lower wear rate than that reinforced with SiC particles. The obtained results at elevated temperatures indicate that at low operating temperature, up to 150 °C, the wear resistance of parent alloy material is higher than that of the reinforced composite materials. At higher temperatures, the composites showed superior wear resistance over the matrix alloy. The composite materials exhibit higher transition temperature than that of the parent matrix materials.

Keywords: Tribology, Composite Materials, Sliding Wear, Wear Patterns, Al_2O_3 Composites, SiC Composites.

INTRODUCTION

Composite materials have been developed primarily for applications requiring stiffness, strength and light weight. Many composites, however, have other properties such as low thermal expansion and high thermal conductivity that make these composites dimensionally stable and resistant to thermal distortion [1]. The search for new materials with specific properties to satisfy tribological applications have boosted the interest of designers and tribologists towards metal matrix composites (MMC). The design requirements of a tribological element are primarily to provide good friction properties as well as high wear resistance, which proved to be difficult to achieve through conventional materials. Composite materials are simply defined as a combination of two or more constituents in a certain configuration on a microscopic scale and with specific properties that combine the best features of each constituent so as to maximize a given set of properties. Generally a composite material consists of a strengthening phase embedded in a matrix.

The metal matrix composite materials MMC can be obtained in many forms such as, aluminum metal matrix and aluminum alloy metal matrix reinforced with graphite fiber, silicon carbide or alumina. These composite materials are promising systems for structural applications. They are competitive for many applications in aircraft, missiles, electric machinery, rocket propulsion system, aerospace and spacecraft applications [2, 5].

The influence of reinforcement on the tribological properties of composites have been investigated by many workers. It has been concluded that, the wear resistance of composite material increases with increase of particle's volume fraction, as a result of the increase of composite hardness by the reinforcement. The wear resistance of the aluminum matrix composites is influenced by numerous factors such as morphology, size and volume fraction of the reinforcing particles [4-9]. In other works, it cannot be concluded that the composite materials invariably show good wear behavior. In some cases the incorporation of reinforcement has been found to produce no significant change in the wear rate. For example, Alpas and Embury [4] carried out tests with block shaped samples of two aluminum alloys and an AL2014 -SiC MMC (20 vol.%, particles 14 μm in size) sliding against a hard steel ring. They have reported essentially the same wear rates for the three materials. They suggested that, the SiC particles caused a reduction in ductility of the material, allowing wear debris to delaminate on a scale comparable with that of the reinforcements by fracture at the particle / matrix interface.

Few workers [1, 3, 5] have investigated the mechanisms of sliding wear in MMCs in detail but the results suggest that these composite materials can exhibit different wear mechanisms under different conditions in exactly the same way as parent metals. Transitions between different mechanisms can then result in large changes in wear behavior for relatively small changes in the operating conditions. Such a behavior is not unexpected and highlights the importance of carrying out wear tests under conditions which simulate as closely as possible the conditions expected in service.

EXPERIMENTAL TECHNIQUE

The influence of the reinforcing ceramic types and their volume fraction on the wear behavior of the sliding pair have been investigated under different operating conditions. Tests at elevated temperatures were conducted to simulate the sliding pair operating at high pressures and temperatures such as bearings of hot rolling stands and piston with cylinder liners in internal combustion engines, where they are operating at high pressures and temperatures ranging from 50 to 80% of the melting temperature of the matrix alloy. A pin on disc experiments have been coducted thrrough the following operating conditions.

Preparation of Specimens

The composites were prepared by stirr casting where particles of Al_2O_3 or SiC, both of 30 μm in size, were added to the aluminum alloy melt at 720 °C. The mixture was stirred using mechanical stirrer and vortex generated from nitrogen gas. The obtained mixture was poured into ingots of 20 mm diameters. The ingots were machined on a center-lathe using tungsten carbide inserts to a 10 mm diameter and 50 mm length. The machined specimens were heat-treated as follows: solution treated at 530 °C for one and a half hour, water quenched, naturally aged at room temperature for 20 hours and then artificially aged at 175 °C for 8 hours. The chemical compositions of the alloy metal matrices are shown in Table 1, and the hardness test results for the aluminum metal matrix and composite materials are shown in Table 2. The chemical composition and mechanical properties of the steel disc are shown in Table 3.

Experimental Conditions

Dry sliding experiments were conducted for different sliding distances up to 600 m, at a constant operating pressure of 0.5 MPa, sliding speed of 1.05 m/sec, and track diameter of 150 mm.

The influence of the operating pressure was studied at different pressures ranging from 0.2 to 4 MPa and a constant sliding speed of 1.05 m/sec, track diameter of 150 mm, and sliding distance of 250 m.

Table 1 Chemical analysis of aluminum metal matrix Alloys

Element	Mg	Cu	Zn	Cr	Si	Fe
Percentage	1.0	0.3	0.3	0.2	0.6	0.7

Table 2 The results of Vicker hardness test for the used composite materials specimens

Composite	Parent	10% Al_2O_3	20% Al_2O_3	10% SiC	20% SiC
HV	120	125	145	130	150

Table 3 Chemical analysis of the disc Material

Element	C.	Si.	Mn.	S.	P.
Percent	0.6	0.9	0.85	0.03	0.025

Table 4 Mechanical properties of the disc material

U. T. S. N/mm^2	720
HV	220

The effect of operating temperature on wear has been investigated at a constant sliding speed, track diameter, operating pressure, and sliding distance. The pin specimen and the steel disc were heated to the test temperature before starting the sliding test. The investigated range of operating temperature is from room temperature to 500°C.

All experiments were conducted after polishing the surfaces of the specimen and the disc to obtain a surface roughness parameter Ra, of 1.15 ± 0.02 μm. The surfaces were subsequently cleaned using acetone to remove any oils or grease. The surface roughness of the disc material and the composite material are shown in Figures 1 and 2 respectively.

Measuring Methods

The weight loss by wear at different test conditions has been measured using a sensitive balance with digital read out having an accuracy of ± 0.001 g. The volumetric wear has been determined from the weight loss and density of each specimen material. The wear rate has been evaluated from the ratio between the volumetric wear and sliding distance.

To investigate the wear patterns, the worn surfaces and the collected debris have been analysed using the scanning electronic microscope and an X-Ray analyzer. The textures of the worn surfaces of the composite specimens and the steel disc have been traced using a Talysurf 6. The average of seven readings of Ra was taken for each specimen.

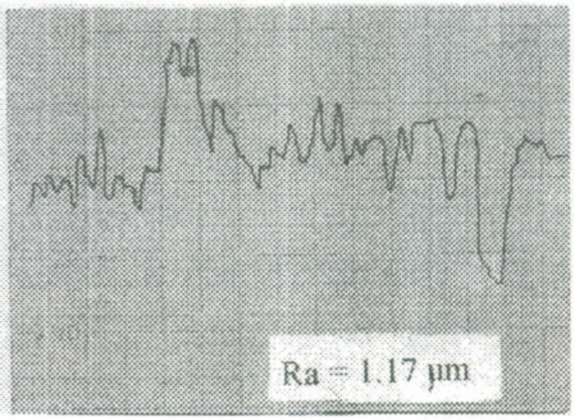

Figure 1 Surafce texture of the steel disc

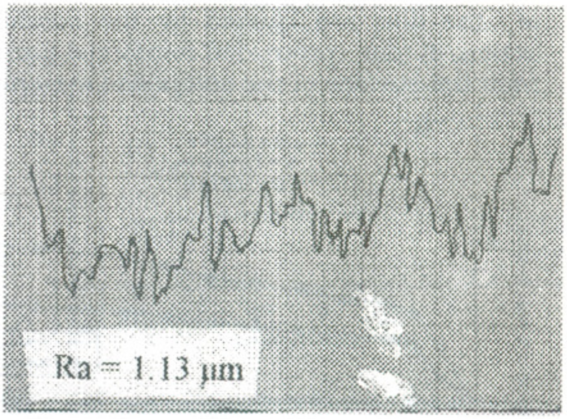

Figure 2 Surface texture of the composite steel disc material pin reinforced with Al_2O_3.

RESULTS AND DISCUSSIONS

Influence of Sliding Distance

The results shown in Figure 3, represent the volumetric wear versus sliding distance for aluminum reinforced with different volume fractions of Al_2O_3 particles. A typical running-in wear regime is observed in the initial 100 m, sliding distance. The increase of the volumetric wear in this regime can be attributed to the abrasive action of the hard steel disc of steel disc abrade the aluminum matrix alloy and induce grooves on the surface of the composite material which have been detected using the scanning electronic microscope as shown in Figure 4. The abraded particles are embedded on the surface of the steel disc, and further scratches the metal matrix and consequently increases the volumetric wear of the composite material. The volumetric wear of steel disc is also increased in this regime as shown in Figure 5. This is due to the protrusion of the ceramic reinforced particles outside the metal matrix surface. These particles are working as a cutting tool and scratches the surface of the steel disc. The surface of the steel disc and that of the composite specimens have been examined using scanning electronic microscope and the results are shown in Figures 6 and 4 respectively. These figures show parallel grooves on both surfaces. The grooves on the composite specimen surface are due to the action of the hard steel asperities on the metal matrix, whereas those on the surface of the disc are caused by the scratching action of the protruded reinforced particles from the surface of the composite material.

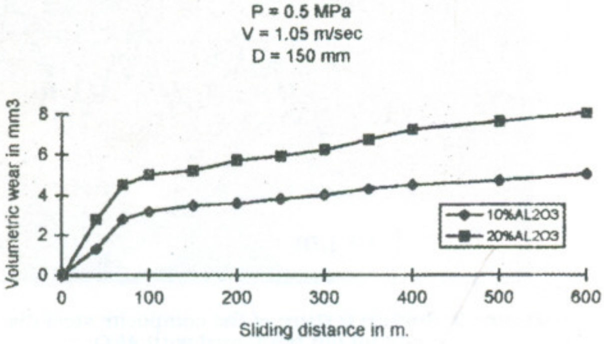

Figure 3 Relation between the wear of composites and the sliding distance.

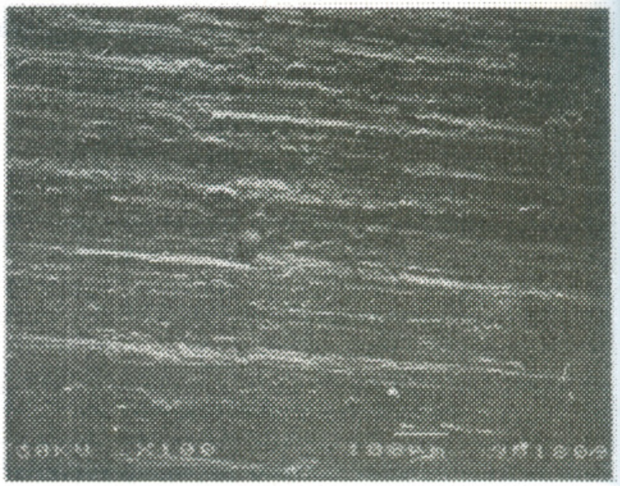

Figure 4 SEM photo for the surface of composite carbon metal matrix reinforced with Al2O3 particles in the running-in regime

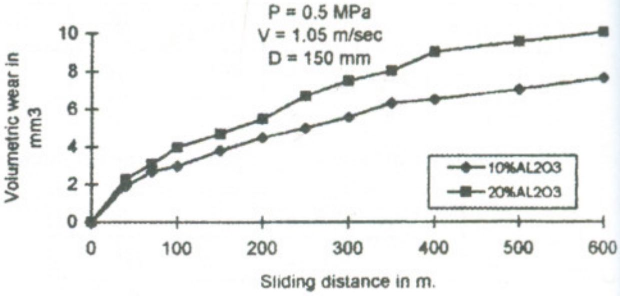

Figure 5 Relation between the wear of steel disc and the sliding distance

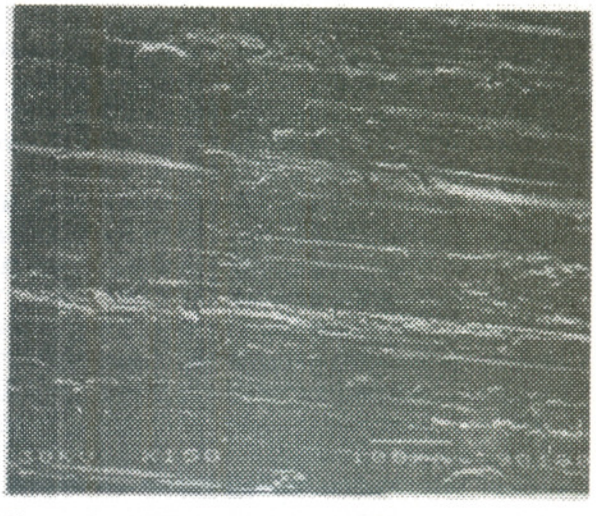

Figure 6 SEM photo for the surafce of high steel disc in the runnin-in regime

Influence of Particles Volume Fraction

The influence of the volume fraction of particles on the volumetric wear has been also investigated and the results are shown in Figure 3. It is noticed from the figure that, the increase of particles volumetric fraction increases the volumetric wear as shown in case of 10% and 20% particle's volume fraction of Al_2O_3. These results were attributed to increase of the number of hard particles which are scratching the steel disc, at high volume fraction. Therefore, the embedded particles in the steel disc are consequently increased. These embedded particles scratch the metal matrix of the composite material, resulting in a separation of the ceramic particles from the surface of composite. This cyclic action accelerates the volumetric wear of both the composite material and the steel disc as shown in Figures 3 and 5 respectively. This cyclic action has been also noticed for specimen reinforced with SiC particles as shown in Figure 7. The scanning electronic micro graph of Figure 8, shows the worn surface of the composite material reinforced with Al_2O_3 particles at high magnification. This Figure shows, parallel grooves with large cavities at different positions. These cavities represent the spaces previously occupied by the separated particles of composite material.

Influence of Operating Pressure

Figures 9 and 10 represent the wear rate versus the operating pressure for different particle volume fractions of Al_2O_3 and SiC repectively. The obtained results show that, the wear rate increases as the operating pressure increases. At low and high levels of operating pressure, it is noticed that, the wear rate increases as the particle volume fraction increases. These results indicate also that, the pressure corresponding to the transition from mild wear to severe wear increases by increasing the particle volume fraction. These results are attributed to, the increase of the number of particles bearing the operating load. Therefore, the load on each particle is reduced and consequently the pressure also is reduced and the transition pressure increases.

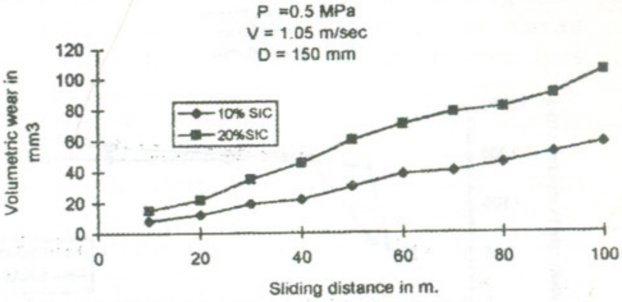

Figure 7 Relation between the wear of composite material and the sliding distance

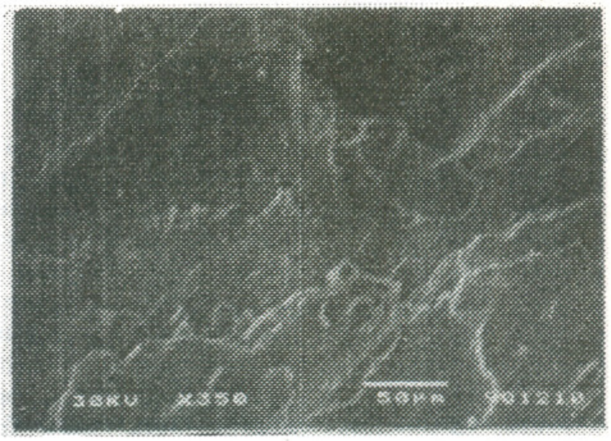

Figure 8 SEM photo for metal matrix surface reinforced with Al_2O_3 particles at high magnification

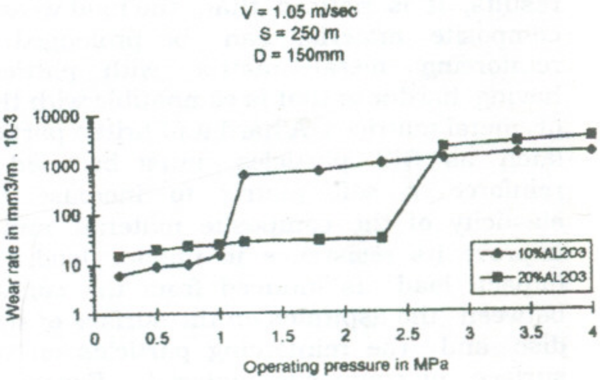

Figure 9 Relationship between the wear rate and the operating pressure

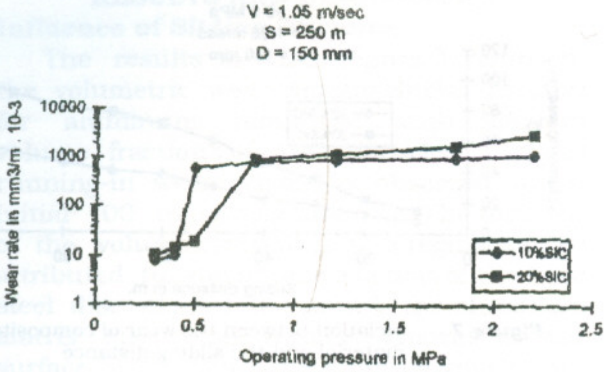

Figure 10 Relationship between the wear rate and the operating pressure.

Influence of Reinforcing Particles Type

The result shown in Figure 10, represents the wear rate versus the opeating pressure for composite materials reinforced with different volume fractions of SiC particles. To investigate the influence of particle type, the obtained results in Figure 9 are compared with those obtained in Figure 10 for composite material reinforced with Al_2O_3 and SiC particles respectively. From these figures, it can be seen that, the transition pressure for Al_2O_3 composites is higher than that for SiC composites. These results are attributed to the higher bond strength of the Al_2O_3 composites than those reinforced with SiC particles. From these results, it is noticed that, the mild wear in composite material can be prolonged by reinforcing metal matrix with particles having hardness that is compatible with that of metal matrices. A hard and brittle particle such as SiC particles must be used to reinforce a soft matrix to increase the elasticity of the composite material and to improve its resistance to impact load. The impact load is induced from the contact between the aspirates on the surface of steel disc and the reinforcing particles on the surface of composite material. Figure 11 shows an SEM photo for metal matrix surface reinforced with SiC particles.

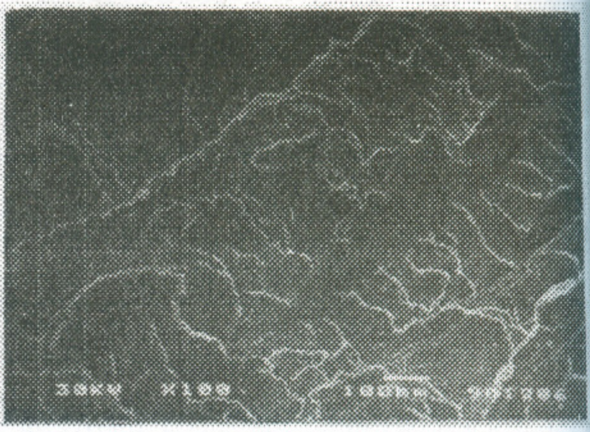

Figure 11 SEM photo for metal matrix surface-reinforced with SiC particles

Influence of Operating Temperature

The obtained results in the pervious sections indicate that, the tribological behavior of composite material reinforced with Al_2O_3 particles is better than that reinforced with SiC particles. Therefore, the behavior of the composite reinforced with Al_2O_3 particles have been studied at elevated temperatures to simulate the operating conditions of sliding pistons and cylinder liners of internal combustion engines and bearing of high speed rolling mills. The results shown in Figure 12, represent the volumetric wear versus the operating temperature for both the parent alloy and the composite reinforced with different volume fractions of Al_2O_3 These results show that, at operating temperature less than 150°C, the parent alloy has smaller wear rate as compared to the composite material and the converse is the case at higher operating temperature. These results are attributed to the effect of the oxidation wear prevailing under these conditions. The oxide layer is formed at the surface between steel disc and the pin. This layer increases as the operating temperature increases, and it works as a lubricant layer reducing the friction and consequently the wear rate in the case of parent alloy. In the case of composite material, the wear rate increases due to the fracture of the contact oxide layer resulting from the effect of the reinforcing particles. This is not the case for parent alloy.

The obtained results indicate also that, the transition from mild wear to severe wear happens at a certain operating temperature, which is influenced by the particle's volume fraction. In the case of parent alloy the transition occurred at an operating temperature of 150°C, while in the case of Al_2O_3 reinforced composite with 10% and 20% particles volume fraction the transition occurs at 300°C and 250°C respectively. This means that, the composite has a higher transition temperature than the matrix. Furthermore, the transition temperature increases as the particle volume fraction increases. These results are attributed to the softening effect of the higher operating temperatures on the metal matrix. Softening reduces the bond strength, and therefore the reinforcing particles are easily separated from the metal matrix, leading to increased wear rate. The number of separated particles increases as the particle volume fraction increases. This explains the higher wear rate of composite material reinforced with 20% particles volume fraction as compared to that of 10% volume fraction.

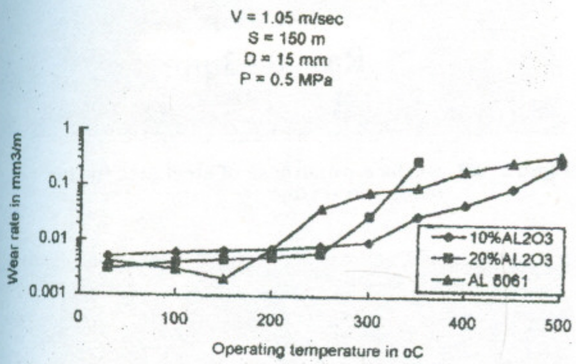

Figure 12 Relationship between the wear rate and operating temperature.

Wear Patterns

The wear patterns in the composite material can be investigated from the results of the wear test experiments and the results of microscopic examinations and X-Ray analyses. These results indicate the presence of three forms of wear pattern, which occur during the experimental work.

Abrasive Wear in The Running-in Regime

Figure 13 shows the result of X-Ray analysis of the collected debris particles. It is found that, the collected particles contain Si, Al, and Fe, where the Fe element is coming out from the steel disc. The surface topography examined by Talysurf 6 for both the steel disc and the composite pin as shown in Figure 14 and 15 respectively. The high roughness observed means that the pattern of wear in the running-in period is one of typical abrasive type.

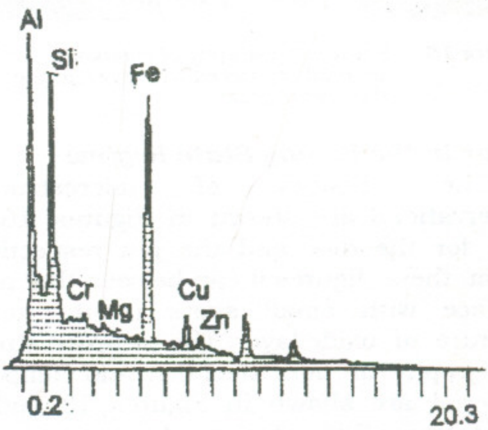

Figure 13 X-Ray analysis for worn debris in abrasive regime

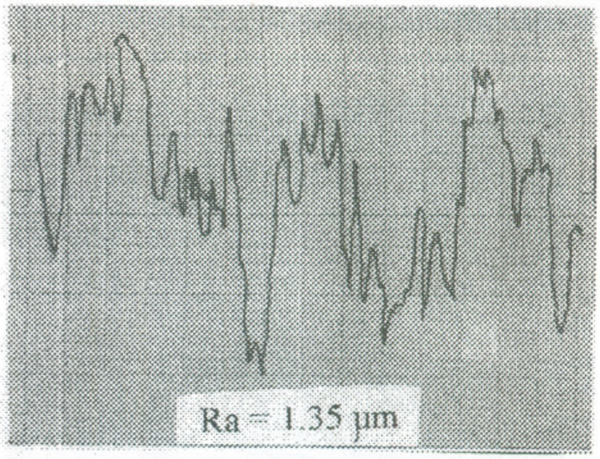

Figure 14 Surface topography of steel disc in the abrasive regime

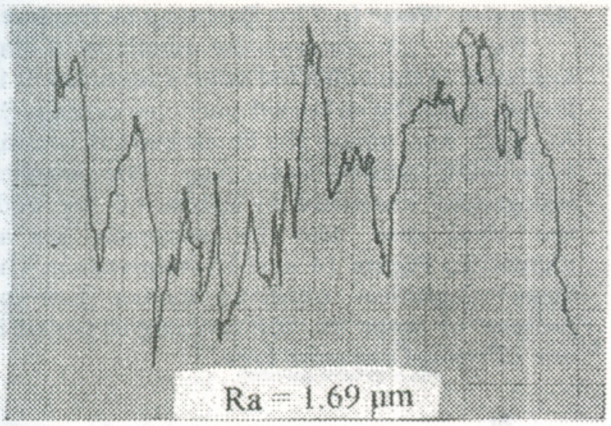

Figure 15 Surface topography of composite material reinforced with Al_2O_3 in the abrasive regime.

Wear in the Steady State Regime

The results of microstructure observations are shown in Figures 16 and 17, for the disc and the pin respectively. From these figures it can be seen that a fine surface with small spots is due to the fracture of oxide layer. The recorded surface topography of both steel disc and composite material are shown in Figures 18 and 19 respectively. These figures show considerable improvement in the surface roughness of both composite pin and steel disc. It can be concluded that, the wear mechanism occurred in that regime is related to the oxidation wear pattern.

Figure 16 SEM photo for the surface of high carbon steel disc in the oxidation regime

Figure 17 SEM photo for the surface of composite material specimens reinforced with Al_2O_3 in the oxidation regime

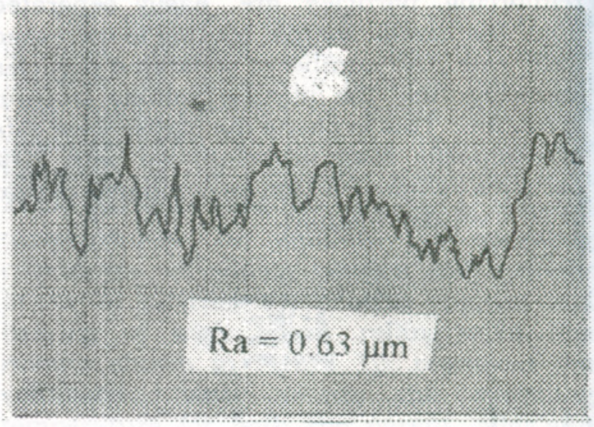

Figure 18 Surface roughness of steel disc in the oxidation regime

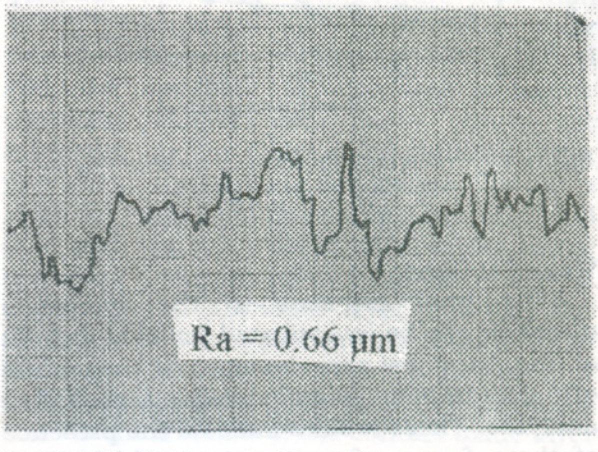

Figure 19 Surface roughness of composite material disc in the oxidation regime reinforced with Al_2O_3 in the oxidation regime

Wear in the Severe Regime

A severe wear has been noticed after the steady state regime, where a sudden increase of the volumetric wear is observed as shown in Figures 9, 10 and 12. At this regime the surface of the steel disc is covered with the worn particles of composite material. These results can be related to the high contact pressure, which induces a higher operating temperature. These contact conditions reduce the hardness of composite metal matrix and consequently the bonding strength is reduced. This condition enhances the welding of composite particles to the steel disc. This means that, the adhesion wear is the wear pattern, which prevails in this regime. Microscopic investigation using the scanning electron microscope, Figure 20, indicates that, a large and flaky debris of the worn composite material surface is covering the surface of the steel disc. The results of the X-Ray analysis showed that the collected debris contains the elements of composite material only as shown in Figure 21. The surface topography shows a very fine surface texture of the composite pin surface as shown in Figure 22.

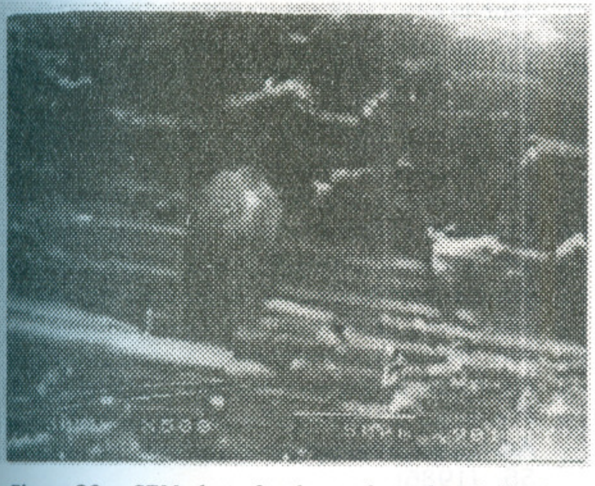

Figure 20 SEM photo for the surface of steel disc in the adhesion wear regime

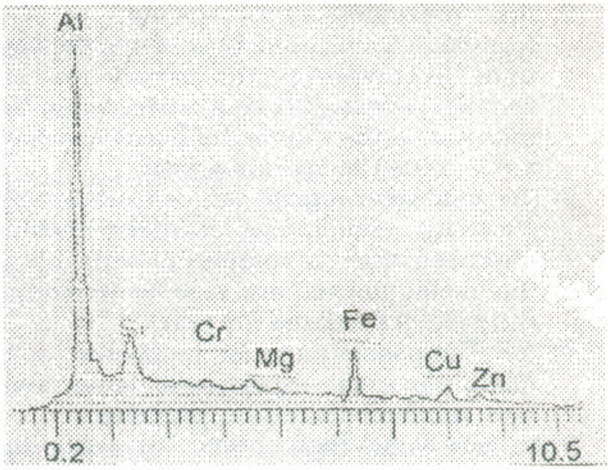

Figure 21 X-Ray analysis for the worn debris in the adhesion regime

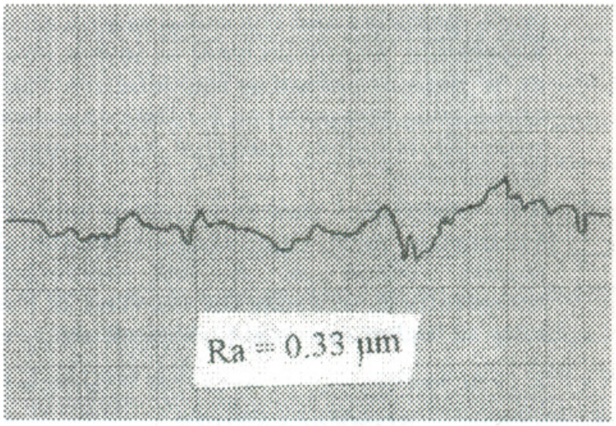

Figure 22 Surface topography of the composite specimen surface in the adhesion regime

CONCLUSIONS

From the results obtained in the present work, the following points are concluded:

1. The wear pattern in the running-in regime is related to the abrasive action of the hard aspirates and reinforced particles. The steady state wears regime is one of oxidation wearing pattern and the severe wear regime is due to adhesion wearing pattern.

2. The pressure corresponding to the transition from running-in to steady state wear increases as the particle volume fraction increase. This is attributed to the increase of the number of particles which are bearing the operating load.
3. The mild wear regime can be extended by choosing reinforcing particles having hardness that is compatible with that of the metal matrix and also by increasing the particles volume fraction.
4. The composite material reinforced with Al_2O_3 particles experiences lower wear rate reinforced with SiC particles.
5. At low and high levels of operating pressure, the rate of composite material of high particle volume fraction is higher than that, of low volume fraction.
6. The composite material reinforced with Al_2O_3 particles and the metal matrix alloy experience from mild wear to severe wear at a certain operating temperature. This transition temperature for the composite material is higher than that for the metal matrix alloy.
7. The composite material has a higher volumetric wear than that of the metal matrix alloys at a low operating temperature, whereas the converse is the case at higher operating temperature.

NOMENCLATURE

P: Operating pressure, MPa
V: Operating speed, m/sec
S: Sliding distance, m
D: Track diameter, mm
T: Operating temperature, °C

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البرى فى الخلائط ذات الأرضية المعدنية

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ملخص البحث

المواد المركبة لها اهمية كبرى فى مجالات الصناعة التى تحتاج الى متانة عالية ووزن خفيف ومعامل احتكاك كبير. وحتى يمكن دراسة المسار الخواص الأحتكاكية للمواد المركبة اجرى العديد من الأبحاث فى هذا المجال وقد اوصت اغلب هذه الأبحاث إلى ضرورة الأبحاث قد تعرض إلى دراسة آليات البرى . لذلك يهدف هذا البحث إلى دراسة آليات البرى عند ظروف تشغيل ودرجات حرارة مختلفة لتحاكى ظروف عمل أجزاء المحركات الميكانيكية وكراسى الانزلاق فى وحدات الدرفلة على الساخن وقد استخدم فى هذا البحث عينات من سبيكة الألمنيوم المقواه بنسب مختلفة من حبيبات السيراميك مثل أكسيد الألومونيوم وكربيد مرحلة البرى العنيف هو برى الالتحام أو الالتصاق وقد استخدم الميكروسكوب الإلكترونى والتحليل الإشعاعى فى استخلاص النتائج. يحدث زيادة فى الحمل الانتقالي باستخدام المواد المركبة وزيادة نسبة حبيبات السيراميك. معدل البرى فى مرحلة بداية التشغيل ومرحلة التآكل العنيف يزداد بزيادة نسبة الحبيبات السيراميكية وعكس هذه النتيجة لوحظ فى مرحلة البرى المنتظم. معدل البرى فى المواد المركبة والمقواة بحبيبات أكسيد الألومونيوم اقل من نظيراها المقواه بحبيبات كربيد السيليكون, وذلك لأن كربيد السيليكون يقلل يخفض قوة الترابط الجزيئى وعلية يسهل انفصال حبيبات السيليكون من سطح المادة المركبة . درجة الحرارة الحرجة يحدث لها تحسن باستخدام المواد المركبة وزيادة نسبة الحبيبات السيراميكية. معدل البرى فى السبيكة الغير مقواه يحدث له انخفاض بزيادة درجة الحرارة حتى درجة حرارة ١٥٠م وذلك لتكون طبقة الأكسيد عند سطحي الانزلاق. أما فى السبائك المقواه يحدث زيادة فى معدل البرى بزيادة درجة الحرارة نتيجة لانهيار طبقة الأكسيد تحت تأثير الحبيبات الصلدة.