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WEAR BEHAVIOR OF LOCAL POLYMER-BASED COMPOSITES

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ABSTRACT

Local Polymer-based Composites were prepared using two different matrix materials. These are GY 250 Epoxy resins with HY 850 hardener and self-curing acrylic local polymers. For each matrix, the reinforcing elements were varied to include particles of Al_2O_3, SiC and CaC_2; and short-carbon fibers. The sliding wear behavior of the matrices and composites were investigated by means of a pin-on steel ring apparatus. Experiments were conducted for varying operating time ranging from 10 to 60 minutes at sliding speeds ranging from 0.4 to 9 m/sec. The contact pressure was altered in the range from1 to 13 bars.

The acrylic polymer experienced considerable wear resistance as compared to the Epoxy. The addition of SiC particles to both polymers showed an adverse effect on wear resistance of the composites. The reinforcement of both matrices by Al_2O_3 enhances the wear resistance of the resulting composites. A remarkable wear-resisting effect has been manifested by the addition of either CaC_2 particles or carbon fibers. For acrylic matrix, CaC_2 and carbon fiber have almost the same improving effect up to a sliding distance of 1800 m. Beyond this distance, carbon fibers proved to have greater improvement as compared to CaC_2. In the investigated range of speed the wear resistance of acrylic- based composite is higher than that of the epoxy-based composite.

The textures of the worn surfaces were investigated using scanning. The predominant wear mechanism in the case of polymers reinforced by carbon fibers occurs by matrix wear and fiber sliding. In case of particles reinforced polymers the wear mechanism is driven by particle fracture and particle-matrix interfacial debonding. The results have been discussed and interpreted.

KEYWORDS
Composite materials, polymers, reinforced polymers, wear mechanisms

1. INTRODUCTION

During the last 25 years, metal-matrix composites (MMCs) have received substantial attention because of their improved strength, high elastic modulus and increased wear resistance over conventional alloys. As reviewed by Durand [1], up to 1995 no investigations on wear behavior of ceramic particle-reinforced polymers were reported in the literature and the use of these materials remained marginal. As described in the review of this reference, ceramic particles filled thermosetting epoxy resins are used extensively as mortar in the construction field, as well as in the fabrication of tools (e.g. deep drawing tools). In this case, the reinforcements used are cheap and easily available particles, such as sand, talc, $CaCO_3$ or similar powders [Masounave; 1994]. Polymer-based model composites were prepared using the conventional thermosetting epoxy resin (Araldite AW 106, hardener: HV 953 U) as a matrix and various ceramics (Al_2O_3, TiC, SiC, TiN, VC, TiO_2 and ZrO_2)as reinforcing agents. The ceramics were added to the resin

before cross-linking [1]. The dry sliding wear behavior of these composites were studied by means of a pin-on-disc apparatus. In these tests, an alumina counterbody was used. The wear mechanisms were studied using scanning electron microscopy (SEM) for observation of wear tracks. Crack formation and particle detachment was identified for the polymer material. The addition of fine ceramic particles to these polymers decreased the wear coefficient down to 1/50.

An overview was given on the friction and wear properties of high temperature resistant polymers, under various testing conditions against smooth steel counterpart [2]. The effect of internal lubricants, and short fiber reinforcements was reported. In addition, the experimental results of sliding wear of polymers reinforced by continuous glass; carbon or aramid fibers were used to develop a hypothetical model composite with optimum wear resistance.

The wear behavior of polycarbonate reinforced with 20 wt. % short glass fibers was investigated [3]. Grooving, cracking, breakage of fibers and debonding of fibers are the major wear mechanisms. As reported by Afaghani [4], fibers made of silicon carbide, aluminum oxide and silicon nitride have been widely used as reinforcement in composite materials, mainly because of their high mechanical properties and fairly low density. These properties are the potential demands in the manufacturing of airplane and aerospace shuttle parts. SiC whisker is characterized by its unique mechanical properties. It has a tensile strength and Vickers hardness of up to 14 GPa and 80 GPa, respectively [4]. As reviewed in this reference, SiC whiskers have been applied mostly as reinforcement in metals and ceramics.

Although plastics reinforced by SiC whisker are too expensive to come into industrial application, SiC whisker-plastic composites can be applied to micro-machine elements. These elements have been attracting the attention of researches in the bio-medical and informatic engineering fields. The mechanical properties of micro-size plastic elements can greatly be improved by the inclusion of SiC whisker [4] .

A model for the abrasive wear of unidirectional fiber-reinforced polymer composites was proposed by Yen and Dharan [5]. The proposed model was cyclic (or quasi-steady state) in nature in which the fiber and the matrix do not always wear at the same rate. According to the proposed cyclic wear model [5], the abrasive wear resistance of a unidirectional fiber composite depends on the volume fraction, wear resistance, and elastic modulii of its constituents. Tribological behaviors of two local polymer-based composites were investigated [6] in dry wear tests. For specimens having fibers oriented normally to test surface, the increase of volume fraction of reinforcing material up to 33% increased the friction coefficient by about 14% and decreased the wear rate by about 95%. The same increase of volume fraction of the reinforcing material increased the friction coefficient by 16% and decreased the wear rate by 65% when the fibers were oriented in the longitudinal and transverse directions [6]. The sliding wear behavior of E-GFRE epoxy reinforced by E-glass a fiber was studied previously [7]. Depending on the normal load and speed, improvements in friction coefficient and wear rate by about 33-62% and 30-70% respectively were achieved when sliding took place against dry clean steel surface. The wear behavior of five grades of thermoplastics against stainless steel counterpart was investigated [8]. Wet sliding wear test indicated that the sliding wear behavior of these polymers are affected by counterface roughness, sliding velocity, interfacial pressure and material type.

Surface temperature is another equally important parameter affecting wear [9-12]. In an investigation conducted by Chang [9], the wear rate of graphite-epoxy was found to increase very sharply at an apparent interfacial temperature of about 250 °C. The results indicate that the

wear rate increases very sharply by increasing the interfacial temperature beyond a certain critical value.

The tribological behaviors of local polymers and some metallic materials were investigated in a recent study [13]. The results showed that, the wear resistance of self-curing acrylic and GY250 and GY257 epoxy resins with HY850 and HY 830 hardeners are higher than those of brass and bronze.

The present study aims at investigating the effect of reinforcement of some of these polymers on the wear resistance of the resulting composites.

2. EXPERIMENAL WORK

2.1 Composites Preparation

Local polymer-based composites were prepared using two different matrix materials. These are GY 250 Epoxy with HY 850 hardener and Self-curing acrylic local polymers. For each matrix, the reinforcing materials were varied to include particles of Al_2O_3, SiC and CaC_2 and short-carbon fibers. Epoxy resin matrix was prepared by mixing the GY250 polymer to the HY 850 hardener with a ratio of 10:6. The composites were prepared by mixing the matrix with the maximum content of the reinforcing materials. Preliminary experiments showed that the maximum possible volume percent of the additives was limited to 28% before the formation of any air bubbles. The mixture of matrix and reinforcing material was carefully stirred using magnetic stirrer, till a homogeneous paste was achieved. The self-curing acrylic composites were prepared by mixing the acrylic powder with 28-vol. % of the reinforcing materials. The solvent provided with the powder was then added at a concentration of 2 gm/ml. The prepared mixtures were poured into cylindrical steel molds of 10 mm internal diameter and pressed at a pressure of 4 bars. To accelerate the curing mechanism the molds containing Epoxy resin composites were heated to 80 °C.

2.2 Wear tests

The dry sliding wear behavior of both the matrices and the composites was investigated using a pin-on steel ring apparatus. The following are the conditions of the tests conducted in the present investigation:

	Parameter		*Value (Range)*
Group A	Sliding time	:	10 – 60 minutes
	Sliding speed	:	1 m/sec.
	Contact pressure	:	8 bars.
Group B	Contact pressures	:	1 – 13 bars.
	Sliding speed	:	1 m/sec.
	Sliding distance	:	210 m
Group C	Sliding speeds	:	0.4 – 9 m/sec.
	Contact pressure	:	8 bars
	Sliding distance	:	210 m

The wear resistance of the matrices and the different composites were evaluated by calculating the weight loss after completion of each test.

2.3 Surface investigation

The texture of the worn surface of the different test specimens was investigated using scanning electron microscope.

3. RESULTS AND DISCUSSIONS

The weight losses of the Epoxy resin and acrylic matrices at test times between 10 and 60 minutes (i.e. distance from 600 to 3600 m) at sliding speed of 1 m/sec. and contact pressure of 3 bars are shown in **Fig. 1**. The acrylic polymer manifested considerable wear resistance as compared to the epoxy. The Brinell hardness numbers of the acrylic polymer and the epoxy resin are HB 30 and HB25 respectively. Therefore, it can be concluded that, the high hardness of the polymer plays an important role in the improvement of wear resistance of this material.

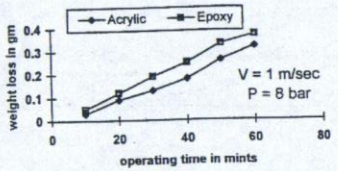

Fig. 1 Weight loss versus operating times for self-curing acrylic and epoxy resin polymers.

Figures. 2 and **3** show the weights loss of the reinforced acrylic and reinforced epoxy respectively after test times ranging between 10 and 60 minutes The results show that, the addition of SiC particles to both polymers has an adverse effect on wear resistance of the investigated composites. The particles were crushed under the effect of applied pressure during the test. This result can be attributed to the high hardness, brittleness and high melting point of these particles (hardness = 2800 kg/mm^2, elastic modulus = 406 GPa and the melting point = 2200 – 2700 ^{0}K) [14] .

The reinforcement of both matrices by Al_2O_3 enhances the wear resistance of the resulting composites. These particles have hardness of 2500 kg/mm^2, elastic modulus of 400 GPa and melting point of 2300 ^{0}K [14]. The values of these properties are lower than those of SiC particles. Indeed Al_2O_3 particles are harder and relatively tougher than SiC particles. These properties improve the wear resistance of the composites.

The thermal conductivities of both SiC and Al_2O_3 were reviewed by Barnard et al. [15]. The values of these conductivities are given in **Table 1.**

Table 1. Thermal conductivities (cal s^{-1} c.n^{-1} ^{0}C^{-1})

Ceramic	Temp., °C			
	37.78	93.33	100	148.89
SiC	0.2148	0.2065		0.2024
Al_2O_3			0.0723	

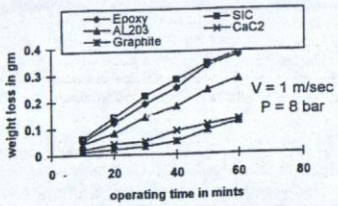

Fig. 2 Weight loss versus operating times for epoxy resin polymers reinforced with different additives

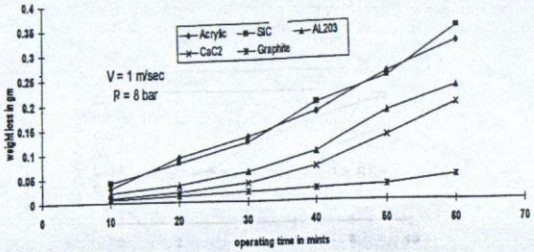

Fig. 3 Weight loss versus operating times for self-curing acrylic polymers reinforced with different additives.

The information reported in this table shows that the thermal conductivity of Al_2O_3 is about one-third of that of SiC. It was also reported that, the values of the specific heat of Al_2O_3 and SiC are 1070 and 670 J/kg.^{0}K respectively [14] . This information means that, Al_2O_3 has lower heat transfer coefficient than SiC and therefor absorbs higher fraction of the heat generated during the sliding wear test as compared to SiC particles. This explains the lower wear resistance of the polymers reinforced by Al_2O_3.

A remarkable wear-resisting effect has been manifested by the addition of either Ca C_2 particles or carbon fibers. For acrylic matrix it was shown that, Ca C_2 particles and carbon fibers have almost the same improving effect up to a sliding distance of 1800 m. Beyond this distance, the addition of carbon fibers proved to have greater improvement as compared to Ca C_2. The high hardness and toughness of Ca C_2 particles play an important role in the improvement of wear resistance of the prepared composites. The coefficient of friction of the acrylic polymer was reduced from 0.25 to 0.1 by adding the carbon fibers. This is due to the lubricating effect of carbon fibers in the solid state. The reduction of coefficient of friction reduces the wear rate.

The weight loss of epoxy polymer, self-curing acrylic polymer and their composites in wear test is shown in **figures. 4** and **5**. The tests were carried out at sliding speed of 1 m/sec, for sliding distance of 210 m. at different contact pressures ranging from 1 to 13 bars. The increase of pressure increases the wear of the two polymers and their composites. The results show that, at low pressure, SiC particles have a small wear-resisting effect. However, at higher pressures, these particles are rapidly crushed and the wear rate is consequently increased. The addition of $Al_2 O_3$ or Ca C_2 particles; or carbon fibers increases the wear resistance of the resulting composite.

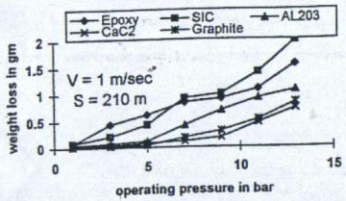

Fig. 4 Weight loss versus operating pressure for epoxy resin polymers reinforced with different additives.

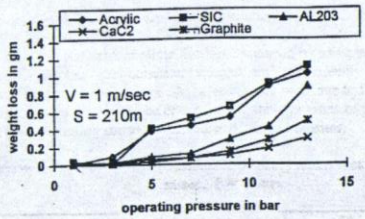

Fig. 5 Weight loss versus operating pressure for self-curing acrylic polymers reinforced with different additives.

Maximum improvement of the wear resistance was achieved by adding the Ca C_2 particles to the considered polymers. This result can be attributed to the high hardness and toughness of these particles. In this case, the abrasive wear mode declined and hence crushing and separation of these particles from the matrices is inhibited. This explains the remarkable improvement of wear resistance achieved by the addition of these particles. The wear-resisting effect of graphite fibers is slightly lower than that of Ca C_2 particles. In this case and as described above, the improvement in the wear resistance of the composites can be attributed to the reduction of the

coefficient of friction and heat generated during the application of wear test. At high pressure, broken graphite fibers were observed. This result can be attributed to the effect of impact load and fatigue stress. The wear-resisting effect of $Al_2 O_3$ particles is lower than that of Ca C_2 particles. The toughness and hardness of these particles play an important positive role in improving their wear-resisting effect. The wear-resisting effect of $Al_2 O_3$ particles can be attributed to the high hardness of these particles and the relatively improved cohesion with the matrices.

The effect of sliding velocity on the weight loss for unreinforced and reinforced epoxy resin and self-curing acrylic polymers are shown in **figures. 6, 7** and **8**. Sliding wear tests were carried out at velocities ranging from 0.4 to 9 m/sec., contact pressure of 8 bars up to a sliding distance of 210 m. The results indicate that, as the sliding speed increases, the wear of unreinforced polymers increases. The results shown in **figures. 7** and **8** for polymer-composites indicate that, the high sliding speed resulted in an increase of the wear of the composites. This result can be attributed to the negative effect of the high temperature resulting from sliding at high speed. This result is in agreement with the results of other investigators [9-12] . In these investigations, the increase of the surfaces temperatures of the composites during the application of wear tests increased the wear rate of the investigated composites.

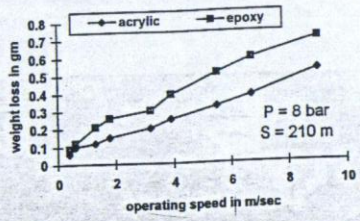

Fig. 6 Weight loss versus operating speeds for epoxy resin and self-curing acrylic polymers.

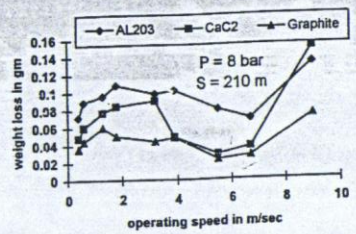

Fig. 7 Weight loss versus operating speeds for epoxy resin polymers reinforced with different additives.

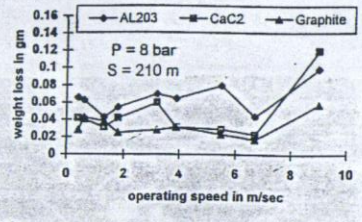

Fig. 8 Weight loss versus operating speeds for self-curing acrylic polymers reinforced with different additives .

In the present study, the wear of polymer matrices leaves the reinforcing particles not surrounded by matrix material. Eventually these unsupported lengths of fibers are subjected to impact load and fatigue stresses as a result of repeated contact with separated debris and asperities of steel ring. These impact loads and fatigue result in premature breakage of these fibers. Therefore, the strong or tough reinforcing particles such as $Ca\ C_2$ have a higher wear resistance than the other brittle reinforcing particles such as $Al_2\ O_3$. Again, using graphite fibers as reinforcing particles, the separated fibers cover the contact surface and acts as a lubricant which reduce both the coefficient of friction and the generated heat. This explains the lower wear rate reported on this composite.

Tables 2. & 3. Lists the percentage improvement in the wear resistance of the prepared composites at different conditions of wear test. Analysis of these results showed that, the wear-resistance of both $Al_2\ O_3$ and graphite fibers is enhanced by using harder matrix (acrylic). The harder matrix can increase the cohesion strength and consequently resist the separation of the reinforcing particles from the matrix. As a result, the wear due to the interfacial debonding is decreased. The main conclusion to be drawn is that, the properties of the matrix material play an important role in determining the wear resistance of the composites.

Table 2. Improvement (%) in wear resistance of composites Wear test conditions: V = 1 m/sec., P = 8 bars

Time, min	30		40		50		60	
Distance, m	1800		2400		3000		3600	
Matrix / Reinforcing Material	Epoxy	Acrylic	Epoxy	Acrylic	Epoxy	Acrylic	Epoxy	Acrylic
$Al_2\ O_3$	29.03	55.55	30.00	48.00	29.629	30.55	26.66	27.27
Graphite fibers	83.87	83.33	80.00	84.00	74.07	87.5	68.33	86.36

Table 3. Improvements (%) in wear resistance of composites. Wear test conditions V = 1m/sec, s = 210 m

P, bar	7		9		11	
Distance, m	1800		2400		3000	
Matrix / Reinforcing Material	Epoxy	Acrylic	Epoxy	Acrylic	Epoxy	Acrylic
$Al_2\ O_3$	52.00	72.727	22.22	50.00	15.15	52.27
Graphite fibers	80.00	81.818	66.66	73.0769	51.515	70.4545

Wear Mechanisms

The textures of the worn surfaces of the composites were investigated using scanning electron microscope. The scanning electron micrographs of the worn surfaces of the epoxy-and acrylic-composites reinforced by $Ca\ C_2$ and graphite fibers are shown in **Figures. 9 & 10** respectively. In these micrographs broken fiber (or reinforcing particle) and fiber/ particle-matrix interfacial debonding are observed. By investigating the worn surface of polymers reinforced by Al_2O_3 after a sliding time of 25 minutes, it was found that the matrix is considerably worn. **Fig. 11** shows the fractured particles and the interfacial debonding. The results of these investigations showed that the mechanisms of wear of the prepared composites are as follows: matrix wear, fiber sliding, fiber or particle fracture and particle-matrix interfacial debonding.

Fig. (9-a)

Fig. (9-b)

Fig. 9 Scanning electron micrographs of epoxy composites :
a) Reinforced by Ca C_2
b) Reinforced by graphite
(Conditions of wear test : v = 1 m/sec . p = 8 bar . t = 25 min.)

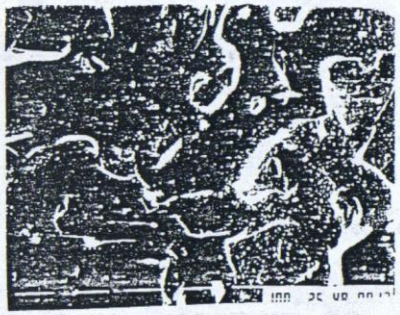

Fig.(10-a)

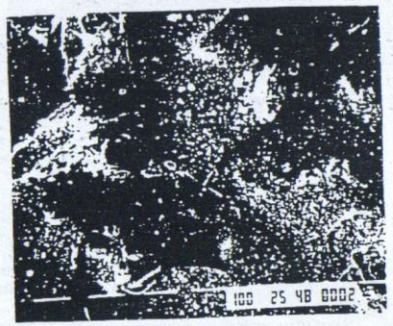

Fig.(10-b)

Fig. 10 Scanning electron micrographs of the worn surfaces of acrylic composite:
a) Reinforced by Ca C_2
b) Reinforced by graphite
(Conditions of wear test : v = 1 m/sec . p = 8 bar . t = 25 min.)

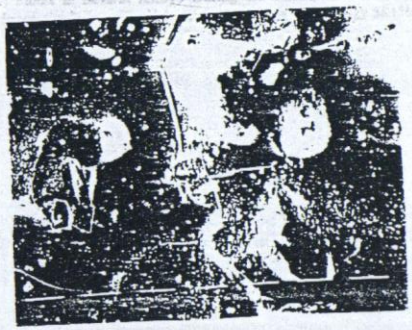

Fig. (11-a)

Fig. (11-b)

Fig. 11 Scanning electron micrographs of the worn surfaces of epoxy- and acrylic- composites reinforced by Al_2O_3
a) Epoxy – composite
b) Acrylic- composite
(Conditions of wear test : v = 1 m/sec , p = 8 bar , t = 25 min.)

4. CONCLUSIONS

The results of the present investigation lead to the following conclusions:

1. Matrix wear, fracture of reinforcing particles and particle-matrix interfacial debonding are the wear mechanisms in the local polymers (GY250 epoxy resin with HY 850 hardener and self-curing acrylic polymers) reinforced by adding either Al_2O_3 or CaC_2. However, in the case of polymers reinforced by graphite fibers, the mechanisms of wear include matrix wear, fiber fracture and fiber sliding.
2. The addition of SiC particles to both polymers decreases the wear resistance of the resulting composites.
3. The reinforcement of both matrices by Al_2O_3 enhances the wear resistance of the resulting composites.
4. A remarkable improvement in wear resistance of the investigated local polymers-composites can be obtained if CaC_2 particles or carbon fibers are used as reinforcing materials.
5. The matrix material plays an important role in determining the wear resistance of the composites. The harder polymer (acrylic) increases the wear-resisting effect of the reinforcing material (Al_2O_3 particles or graphite fibers).

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