

## **WEAR RESISTANCE OF THERMOPLASTIC COATINGS**

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### **ABSTRACT**

Abrasions wear caused by sand particles is the prevailing mode of wear in the Arabic nations. The relative increase in the concentration of airborne dust is responsible for the wear increase. It is important to know that the abrasive wear represents more than 50% of all other types of wear due to the spread of sandy regions. Therefore, there is an increasing demand to develop the abrasion wear resistance of the polymeric coated surfaces to withstand the abrasive action of sand particles.

Experiments were carried out to investigate the abrasive wear of the test specimens caused by sand particles. Low-carbon steel and hardened steel specimens as well as specimens coated by thermoplastic composites were tested. Silicon oxide ( $\text{SiO}_2$ ), aluminium oxide ( $\text{Al}_2\text{O}_3$ ), iron, copper and glass fibre were used as filling materials in polyamide (PA6). Low-carbon steel was used as substrate. An abrasive wear tester was constructed to the wear caused by sand particles.

PA6 showed promising results, especially if both the concentration and grain size of the additives were carefully selected. The addition of iron and  $\text{Al}_2\text{O}_3$  powders to PA6 showed a considerable mitigation in the wear process if their concentrations were controlled to a certain limit. The reinforcement used in the polyamide coatings were metallic wires, polypropylene and polyamide fibres. Also, filling polyamide coatings by copper, iron, molybdenum disulphide and graphite at concentration of 10 wt.% was tested. The polyamide coatings have been impregnated by 10 wt.% and 20 wt.% of SAE 30 oil.

Besides, polyamide coatings filled by 10 wt% iron powder and impregnated by 10 wt.% oil showed significant wear resistance. Also, polyamide fibres as filling material in polyamide coatings enhanced the abrasive wear resistance. This enhancement increased with increasing the fibre concentration and decreasing the fibre diameter. Tin coated steel wire as short fibres reinforcing polyamide coatings gave the minimum wear.

### **KEYWORDS**

Wear, sand particles, polyamide, coating, metallic wires, metallic powder, oil.

## INTRODUCTION

Abrasive wear of engineering surfaces caused by sand particles represents a major problem, and there is an increasing demand to develop materials of high wear resistance to save energy and reduce wear losses in different engineering applications. The subject of abrasive wear of polymer matrix composites has received attention over the past four decades. The increased interest in this area aims to use polymeric composites in aerospace, transportation and process industries, in which they can be subjected to multiple solid or liquid particle impact, [1 - 4] where durability is a prime consideration. Typical examples of dusty environments where polymer composites are applied are belt conveyors and pipelines carrying sand, slurries in petroleum refining, helicopter rotor blades, pump impeller blades, high-speed vehicles and aircrafts, water turbines and aircraft engine blades. Differences in the erosion behaviour of various types of polymer matrix composites are caused by the content, type, orientation and properties of the reinforcement on the one hand and by the type and properties of the matrix and its adhesion to the fibers/fillers on the other, [5 – 8]. The effect of fiber reinforcement has been classified in importance as fiber material, fiber content, reinforcement type (i.e., length, diameter etc.) and fiber orientation, [9]. The material with the strongest interface strength showed the best abrasion resistance. Generally composites with thermosetting matrix wear in a brittle manner. A totally different scenario is observed in the thermoplastic matrix composites. It was reported that, the rate of material loss, of glass-polyester composites filled with different particulate fillers such as fly ash, aluminium oxide ( $\text{Al}_2\text{O}_3$ ) and silicon carbide (SiC) significantly reduced with the addition of hard particulate fillers into the matrix, [10, 11]. The composites with  $\text{Al}_2\text{O}_3$  filling showed better erosion resistance than the composites filled with SiC and fly ash.

Tillage tools are made of low-carbon steel, which may be heat treated and hardened, or high-carbon steel [12]. Unfortunately sand particle impacts and contacts often cause catastrophic failure of these materials. Alternative wear resistant materials with improved fracture toughness and design of rigidly supported inserts should be investigated. It is well known that, the tillage tools require strength and toughness to resist impact, and hardness to resist wear, [13]. Cast irons have good wear resistance, but relatively poor toughness, while steels have adequate strength and toughness, but relatively poor wear resistance. A metallic-glass coating could be used to increase the hardness of the steels and retain the softer core to help absorb impacts.

The effect of the sand constitution on the abrasive wear resistance of a heat treated high carbon steel was investigated, [14, 15]. The abrasive wear resistance of such steels was found to increase with hardness in both sandy and clay soils. In soils containing considerable amounts of large stones the wear resistance for all heat treated steels was similar. Wear rates were found to be twenty times higher in stony soil than in sandy soil and seven times greater than in clay soil.

Thermoplastics are known for their abrasion resistance, accompanied by high thermal expansion coefficient, low compressive yield strength and poor heat conductivity. Bonding

thermoplastic to a steel substrate, or adding suitable fillers can improve its mechanical properties, heat conductivity and lubricity, [16 - 18]. Experiments were carried out to investigate the abrasive wear of tillage tools coated by thermoplastic composites, [19, 20]. Polyamide coatings showed promising results, especially if both the concentration and grain size of the filling materials were carefully selected. The addition of iron and aluminium oxide powders to polyamide showed a considerable reduction in the wear process if their concentrations were controlled to a certain limit.

Abrasive wear resistance of polymers is an important property for engineering applications specially in automotive industry, [21]. Abrasive wear resistance of polymers depends mainly on the nature of the polymer itself and the operating parameters such as applied load, shape, size and the nature of abrasive particles, its attack angle, scratch velocity, state of the interfacial lubrication.

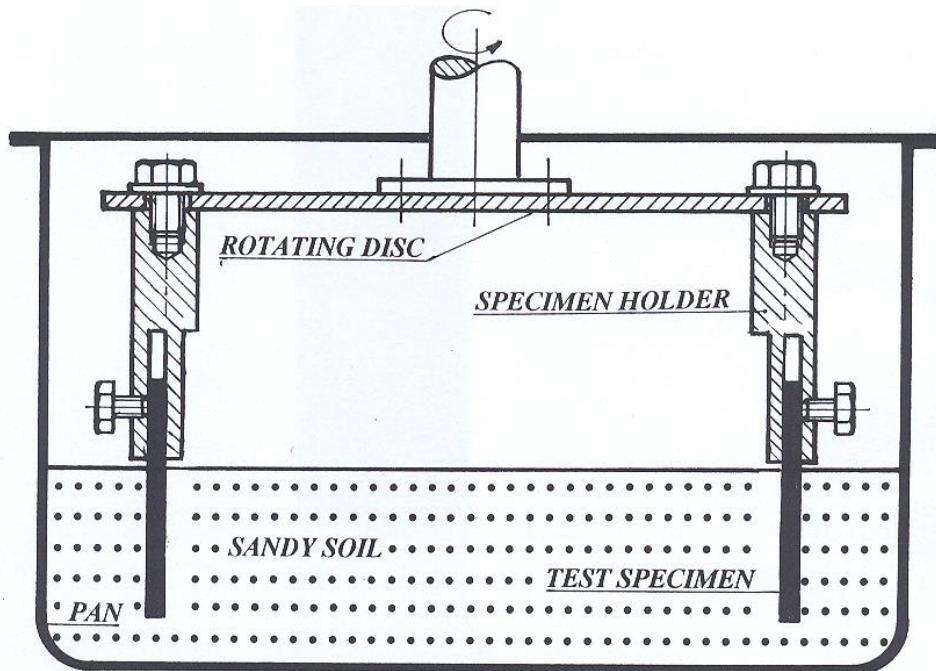
The controlled version of abrasive wear caused by sand particles is the scratch tests. Several papers are available reporting on the influence of operating parameters on the scratch hardness of polymers [22 - 28]. The influence of indenter geometry, test temperature, loading rate, and strain rate on the scratch behaviour of PMMA was investigated, [29]. The effect of indenter geometry and test temperature on the friction behaviour of UHMWPE in single point and multi asperity scratch tests were studied, [30]. It was observed that the friction coefficient increased with increasing the indenter attack angle for the single point scratch test. The abrasive and erosive wear behavior was studied.

In the present work, polyamide and polyethylene was used as thermoplastic coatings on low carbon steel substrates. Comparative tests were carried out using an abrasive wear tester which simulated the rubbing conditions between the sand particles and moving surfaces.

## EXPERIMENTAL

An abrasive wear tester was constructed to simulate the working condition of wear caused by sand particles. It consists of a rotating disc carries eight specimen holders, Fig. 1. The specimen was in form of low carbon steel sheet of 1.0 mm thickness, 30 mm width and 100 mm length. The specimen was coated from one surface where every two specimens were fixed back to back and assembled in the specimen holder so that the coated surface was adjacent to the sand contained in the cylindrical container. A variable speed electric motor derived the rotating disc. The reinforcements used in this experiments were wires of 5 mm diameter and 10 mm long of copper (30 VHN), mild steel (129 VHN) and spring steel (330 VHN) as well as tin coated steel wires of 0.3 mm diameter. The thickness of the tin coating was 0.03 mm. Also, short fibres produced from polyamide (PA6) of 0.1, 0.3 and 0.5 mm diameter were used as filling material in polyamide coating at concentrations of 10, 20 and 30 wt.%. The length of these fibres was 10 mm. Polyamide coatings filled by copper, iron, molybdenum disulphide and graphite at concentration of 10 wt.% and filled by 10 and 20 wt.% of SAE 30 oil were tested. The particle size of copper and iron powder was ranging from 30 to 50  $\mu\text{m}$  while molybdenum disulphide and graphite had particle sizes of 5 to 10  $\mu\text{m}$ . To increase the abrasion

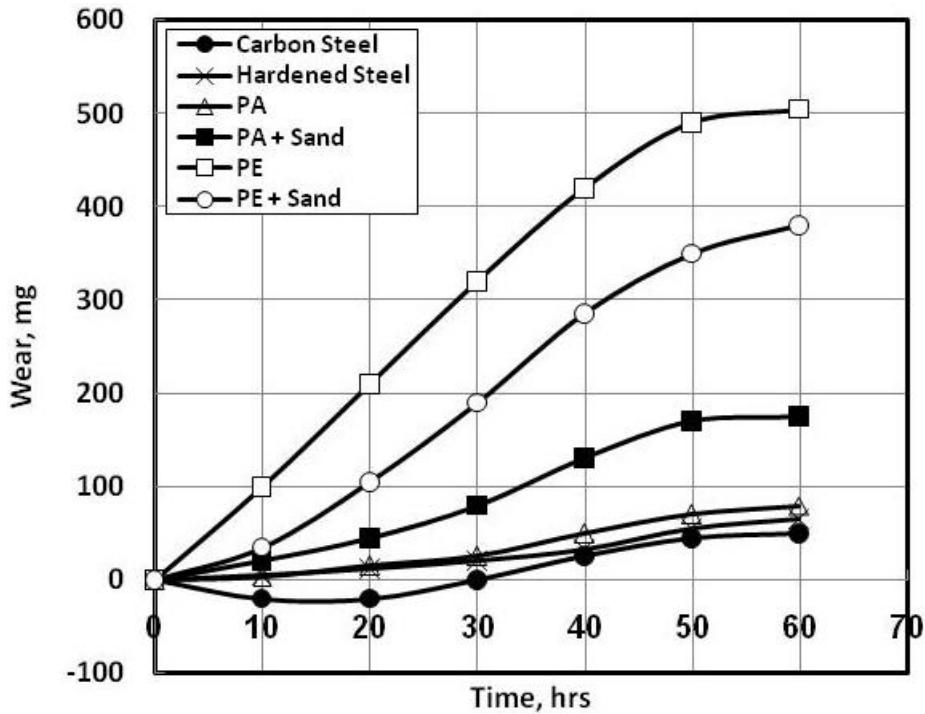
resistance of thermoplastic coatings to withstand wear caused by sand particles, sand ( $\text{SiO}_2$ ) was added to the thermoplastic coating as filling materials at a concentration of 10 wt. %. The sand was of Air Cleaner Fine Test Dust (ACFTD) with particle size ranging from 0 to 80  $\mu\text{m}$ . The rest of the specimens were chosen in such a way that one of them was high carbon steel (0.45% C, 0.25% Si, 0.65-Mn) of 380 HV hardness and the other was of low carbon steel (0.12% C, 0.25% Si, 0.37% Mn) of 119 HV hardness. The steel specimens were used as reference materials. The polyamide in form of powder from 50 to 80  $\mu\text{m}$  particle size was distributed on the surface of the substrate after reinforcing by the metallic wires. The thickness of the powder was adjusted to be 1.0 mm. Then the substrate was heated by a hot plate until the melting of the polyamide coating. The surface roughness of the coating was about 3.2  $\mu\text{m}$ .



**Fig. 1 Layout of the abrasive wear tester.**

## RESULTS AND DISCUSSION

The results are shown in Fig. 2 for tests up to 60 h. It is shown the best of the results was recorded for low-carbon steel. The specimens coated by PE and PE filled by sand gave the highest wear loss. The specimens covered by polyamide-based coatings gave good wear results as compared with mild steel. Furthermore, the high carbon steel specimen gave wear values which were greater than that of low-carbon steel and approaching that displayed by polyamide coatings. The results of polyethylene coatings came last in rank after high carbon steel.



**Fig. 2 Wear of the test specimens.**

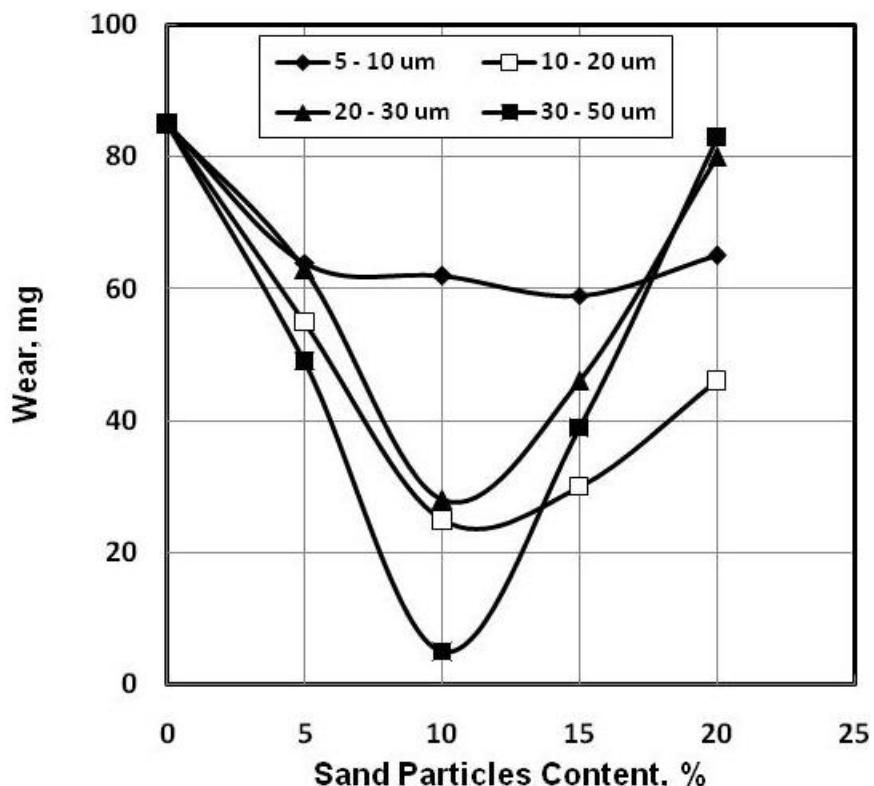
Comparing the wear results of both polyamide and polyethylene filled by silicon oxide ( $\text{SiO}_2$ ), it is shown that, although the content of  $\text{SiO}_2$  was the same, the wear loss was four times as high for polyethylene as for polyamide. This may be attributed to the low abrasion resistance of polyethylene compared to polyamide or to the low compatibility of  $\text{SiO}_2$  with polyethylene. The low compatibility of  $\text{SiO}_2$  with polyethylene may properly lead to the detachment of  $\text{SiO}_2$  due to its poor adhesion.

Low carbon steel showed the best abrasion results where sand particles were embedded on the surface of the specimens and consequently increased their abrasion resistance. Polyamide showed nearly equivalent results because of its high abrasion resistance and its ability to deform plastically without greater material removal.

Finally, the wear results of both low and high carbon steel indicated that low carbon steel was more effective in combating abrasive wear. Low carbon steel showed negative wear results up to 30 h due to the embedment of sand particles on the steel surface, after which a positive wear was recorded. High carbon steel showed negative wear results up to 4 h due to sand embedment, after which increased wear was observed. This behaviour is strongly related to the wear mechanisms accompanying the wear process in mild and high carbon steels.

The embedment of the abrasive sand particles in the surfaces of the steel specimens offers an explanation for the observed initial increase of weight recorded for both low and high

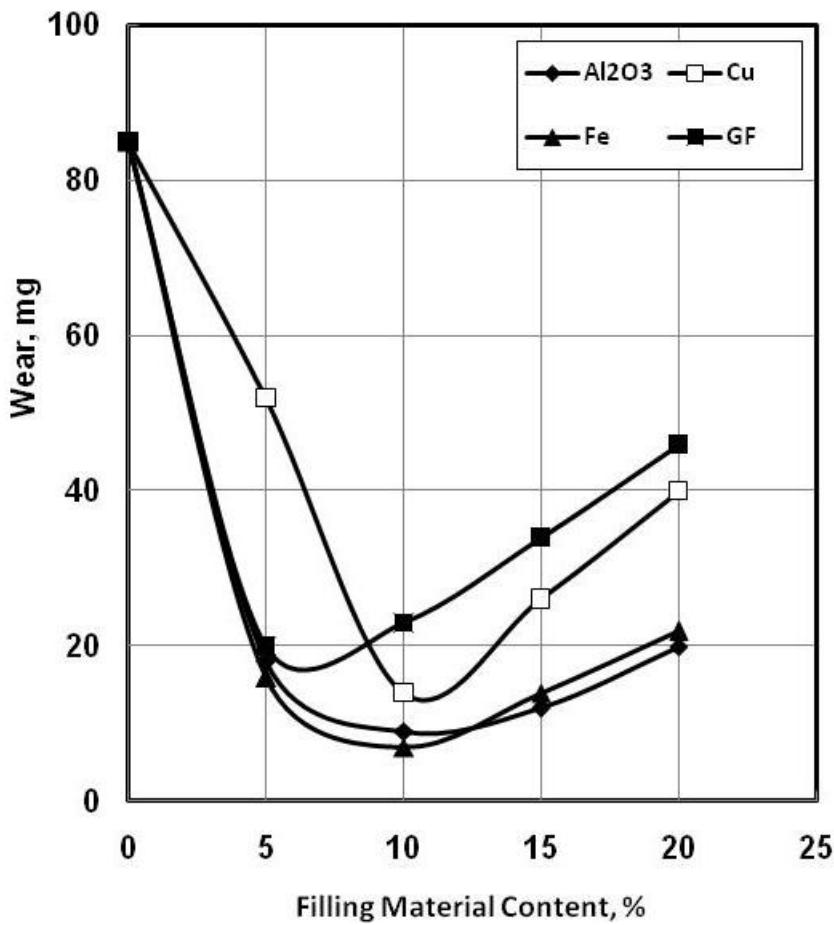
carbon steel. The microscopic examination of the mild steel surface confirmed the presence of the sand particles embedded on its surface. As a consequence of these results, it was decided to study the effect of both silicon oxide grain size and content on wear of composite coatings. PA6 was chosen to form the polymer content of the composite. Four groups of samples were prepared. The first group was filled by silicon oxide with grain size ranging from 5 to 10  $\mu\text{m}$  in four contents (5, 10, 15 and 20 wt. %). The second, third and fourth groups were filled by silicon oxide with grain size (10 - 20  $\mu\text{m}$ ), (20 - 30  $\mu\text{m}$ ) and (30 - 50  $\mu\text{m}$ ) respectively. The experimental results shown in Fig. 3 were recorded after 16 hours. The best results were displayed by the large size (30 - 50  $\mu\text{m}$ ) and at a silicon oxide content of 10 wt. %. The results observed for silicon oxide content of 20 wt. % and the size (10 - 20  $\mu\text{m}$ ) came second in rank.



**Fig. 3 Wear of polyamide coated specimens filled by sand of different particle sizes.**

A further investigation was undertaken to show the effect of adding fillers of different materials on wear of PA6, Fig. 4. The fillers were iron, copper, aluminium oxide ( $\text{Al}_2\text{O}_3$ ) and glass fibres, and all were added to PA6 by weight to form four contents of 5, 10, 15 and 20 wt. %, with a test time of 16 h. The particle sizes of iron, copper and aluminium oxide were (75 - 95  $\mu\text{m}$ ), (80 - 100  $\mu\text{m}$ ) and (50 - 70  $\mu\text{m}$ ) respectively, while the glass fibres were of 70  $\mu\text{m}$  diameter and (1 - 2 mm) length. As for polyamide coating filled by iron, copper and  $\text{Al}_2\text{O}_3$ , wear was observed to decrease down to a minimum at 10 wt. % filling material content, then rose again as the content increased. Glass fibres filled coatings showed relatively low values of wear at 5 wt. % content, but as the content increased wear tended to

increase. Best results were obtained using iron as filler to PA6 at 10 wt. % content. With aluminium oxide the results at 10 wt. % material additive came second in rank.



**Fig. 4 Wear of polyamide coated specimens filled by the powder of aluminium oxide, copper, iron as well as glass fibres.**

As shown in Figs. 3 and 4, wear at 10 wt. % content was lower than those observed at the other contents. The exceptions were with glass fibres and silicon oxide of grain size ranging from 5 to 10 µm. However, a typical reduction in wear was observed at 20 wt. % silicon oxide with the smallest grain size (5 - 10 µm).

To seek an explanation for the wear phenomena observed during the above mentioned tests, the following must be considered:

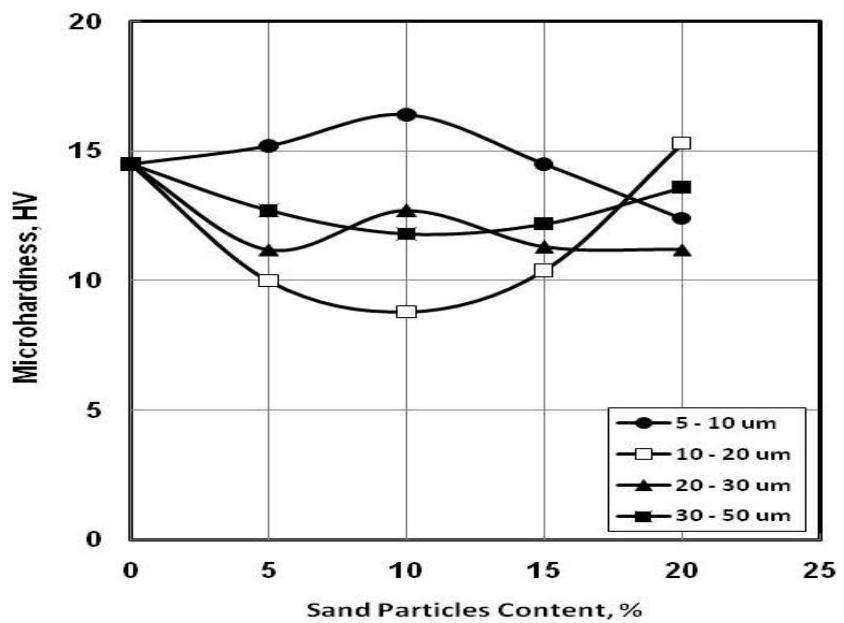
- the effect of the adhesion force generalized between the polymer matrix and the filling materials,
- the hardness of the filling materials contributed to the composite strength, the hardness of the polymer matrix, which is strongly correlated to the rate of polymer cooling. The rate of polymer cooling depends on the thermal capacity of both the filling materials and the coated surfaces as well as the content and size of the fillers,

- the embedment ability of the polymer matrix, which depends mainly on its hardness.

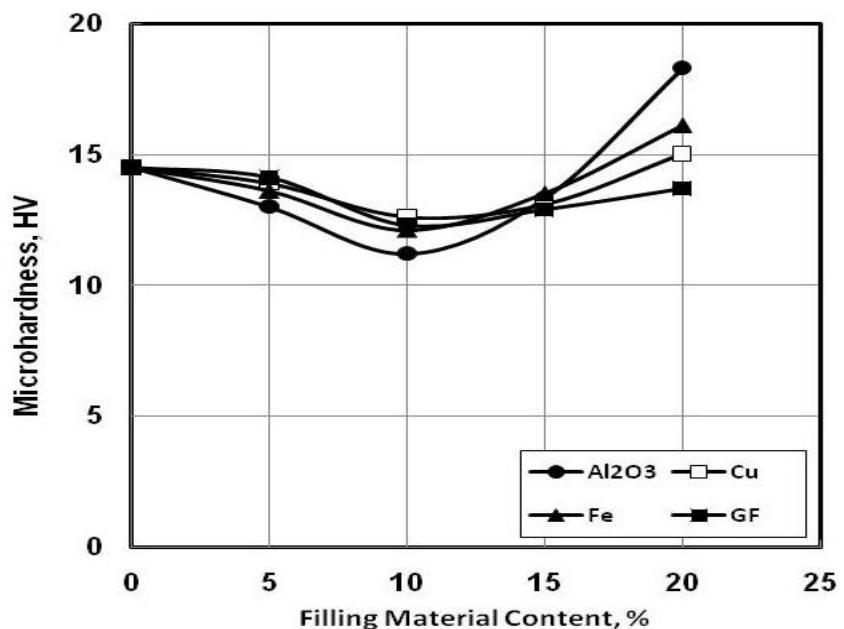
Therefore, to explain the wear data recorded in the tests undertaken, a microhardness tester was used to measure the Vickers hardness of all the samples used in the study, Figs. 5, 6. As a general trend, the hardness measurements showed that the low wear values were always compatible with the low hardness. Furthermore, a possible explanation for the general decrease in wear observed at 10% filler content ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , Cu, Fe) could be related to the low hardness of the polymer matrix, Figs. 5 and 6, which enables the hard sand particles to be easily embedded in the surface of the polymer and to increase its abrasive resistance and protect the thermoplastic surface from more wear. At 20 wt. % filler content a general increase in wear was observed. The reason for this can be attributed to the weak adhesion of the fillers with polymer matrix as well as the reduction of the filler's free polymer surface areas and its relatively high hardness. The latter two reasons result in the weak ability of the polymer surface to embed sand particles and adversely affect the wear resistance. Glass fibre showed an increasing wear trend owing to the weak adhesion of its fibres in the polymer matrix, Fig. 4. The adhesion decreased as the filler content increased. The measurements of the hardness over the surface of the composite filled by glass fibre indicated slight changes of hardness values with increasing glass fibres content, Fig. 6.

The effect of addition of copper, iron, molybdenum disulphide and graphite powders to polyamide coatings filled by oil is illustrated in Fig. 7. Filling polyamide coatings by oil significantly improved the abrasive wear resistance. That improvement may be attributed to the presence of infinite number of voids on the plastic matrix representing a continuous supply of oil. As the abrasive particles abrade the coating the oil gets into the friction surface, forms low shear film and reduces friction and wear. Besides, presence of oil retarded the embedment of sand particles in the polyamide matrix. Iron and graphite filled polyamide coatings displayed the lowest values of wear at 10 wt. % oil content. Further increase of oil content significantly increased wear. Molybdenum disulphide filled coatings showed a decreasing trend of wear with increasing oil content, where the lowest wear was observed at 20 wt. % oil content.

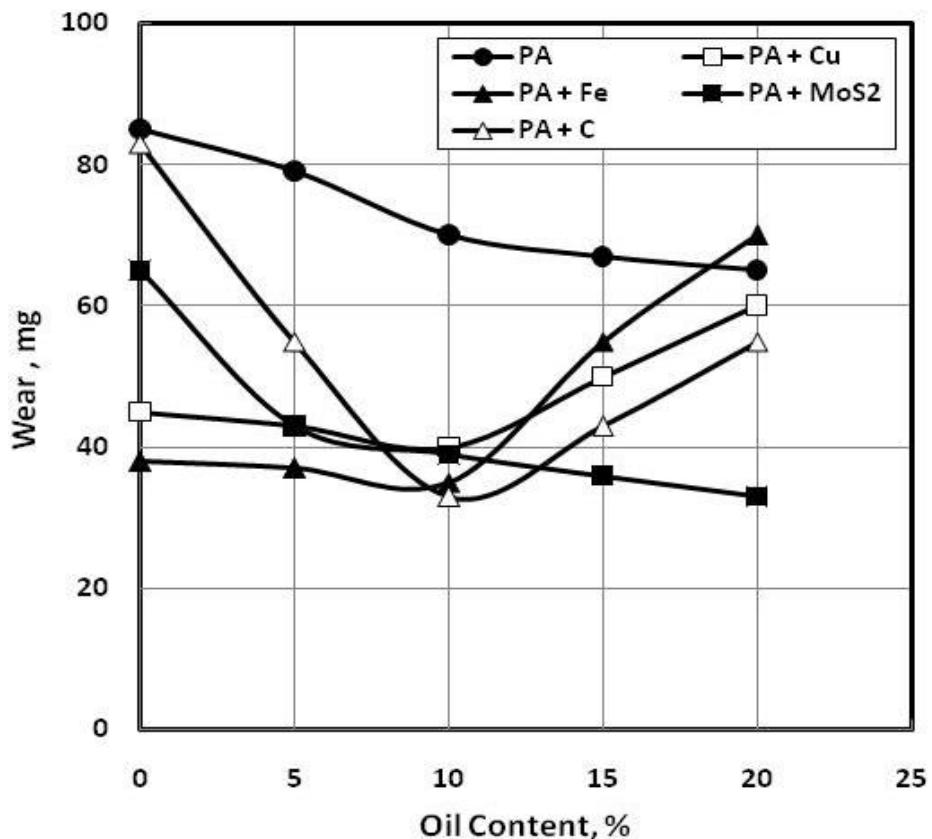
Reinforcing polyamide coatings by short fibres of PA6 was achieved to develop the mechanical properties of the coatings. It was observed that wear decreased with increasing the fibre diameter of PA6 and increasing their content, Fig. 8. The best results were observed for PA6 fibres of 0.5 mm diameter and 30 wt.% content. The uncoated steel specimens represented more wear than polyamide coated ones. A possible explanation for the wear reduction observed for polyamide coatings could be related to their low hardness which enables the abrasive particles to be easily embedded in the surface and to increase its abrasive resistance and protect the surface from more wear. Presence of fibre reinforcement can restrain the deformation of the polyamide matrix where the external load applied through the matrix was directed to the fibres by shear at the interface. Besides, plastic deformation, grooving and smearing of surface caused by abrasive particles can be reduced due to strengthening effect of the fibres.



**Fig. 5** Microhardness of polyamide coated specimens filled by sand particles.

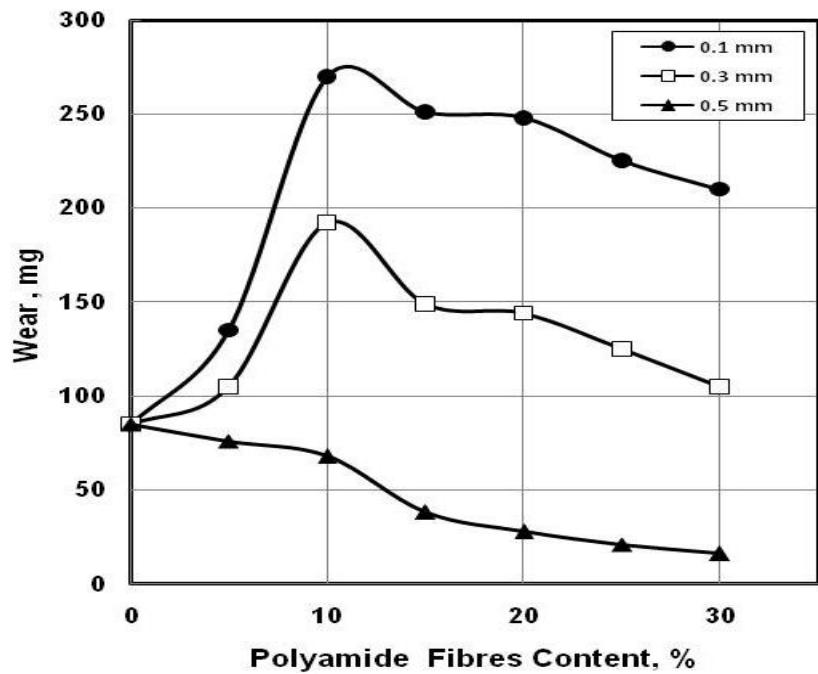


**Fig. 6** Microhardness of polyamide coated specimens filled by the powder of aluminium oxide, copper, iron as well as glass fibres.

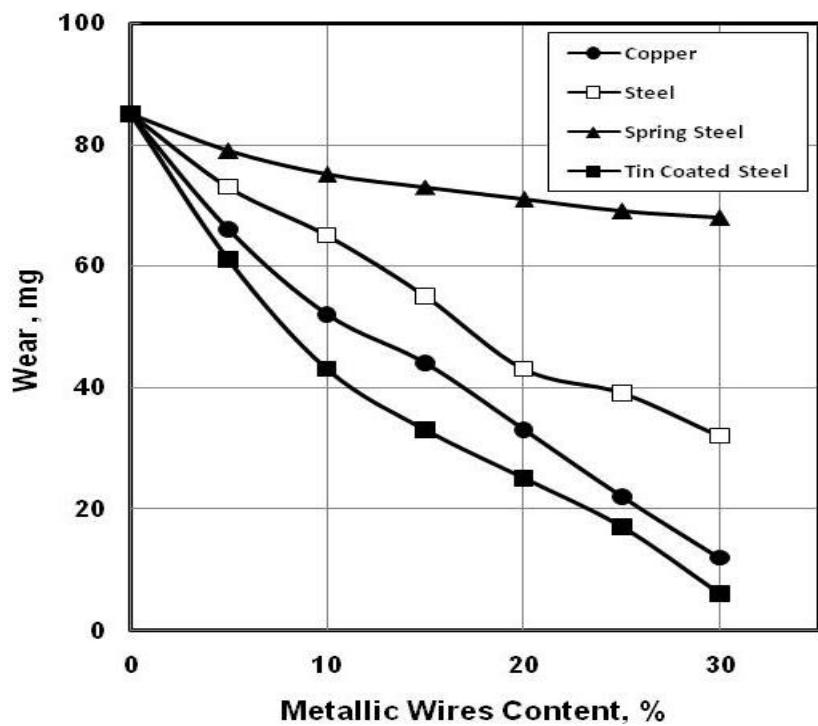


**Fig. 7 Wear of polyamide coated specimens filled by oil as well as the powder of copper, iron, graphite and molybdenum disulphide.**

Tin coated steel short wires reinforcing polyamide coatings showed quite good wear resistance. Minimum wear was observed at 30 wt. % wire content. Copper wires showed relatively higher wear followed by steel and spring steel, Fig. 9. Based on that observation, it can be recommended to reinforce polyamide coatings by metallic wires of relatively low mechanical properties. This behaviour confirmed the fact that difference between shear strength of parent and reinforcing material is critical to have good bond between them and consequently the separation of the fibres from the parent materials would more difficult. In the present study, tin played the role of reducing the difference of the mechanical properties. It is suggested to perform further experimental work in this area to investigate that effect.



**Fig. 8 Wear of polyamide coated specimens filled by oil and reinforced by polyamide fibres of different diameter.**



**Fig. 9 Wear of polyamide coated specimens reinforced by metallic short wires.**

## **CONCLUSIONS**

A study on wear of test specimens caused by sand particles was considered. The study attempted to reveal the effect of coating the test specimens with polymer filled by material additives. The thermoplastic coatings recommended in this work gave a relatively soft matrix of plastic materials, which enhanced the embedment of sand particles. The embedment increased the abrasion resistance of the coatings appreciably, by forming a protective layer of hard sand particles on the surface of coatings. As the hardness of the plastic matrix decreased, the sand particle embedment increased, allowing for the growth of the protective layer of the friction surfaces. The minimum hardness of the plastic matrix was observed for coatings containing 10 wt.% of filler concentration. PA6 showed good wear results when in contact with sandy soils. Polyamides filled with silicon oxide of grain size ranging from 30 to 50 µm and a concentration of 10% were found to combat the incidence of wear in a sandy medium. Furthermore, the addition of iron particles and aluminium oxide ( $\text{Al}_2\text{O}_3$ ) to PA6 enhanced the abrasive resistance of the composite.

In addition, it was found that polyamide coatings filled by 10 wt.% oil as well as 10 wt.% iron, graphite, molybdenum disulphide and copper showed significant wear resistance. Polyamide fibres as filling material enhanced the abrasive wear resistance. This enhancement increased with increasing the content and the fibre diameter. Tin coated steel wire as short fibres reinforcing polyamide coatings gave the minimum wear rate. Reinforcing polyamide coating by metallic wires can decrease the hardness near the wire, where the cooling rate is faster. This behaviour can be useful to resist abrasive wear caused by sand particles where the relatively soft matrix will be embedded by sand particles and their abrasion will be reduced. Besides, wear decreased as the hardness of reinforced metallic wires decreased. It seems that the shear strength at the fibre matrix interface increased as the hardness difference between the fibre and the matrix decreased.

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