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Erosive wear behaviour of polyphenylenesulphide (PPS) composites

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Abstract

The solid particle erosion behaviour of randomly oriented short glass fibre and mineral particle reinforced polyphenylenesulphide (PPS) composites has been characterised. The erosion rates of these composites have been evaluated at different impingement angles (15–90°) and at three different particle speeds ($v = 20$, 40 and 60 m/s). The particles used for the erosion measurements were silica sand with a diameter of 150–200 μm. Mass flow of sand was 9 g/s, which is impinged under 4.5 bar pressure. The PPS composites showed semi-ductile erosion behaviour, with maximum erosion rate at 60° impingement angle. The impingement angle has a significant influence on erosion rate. The morphology of eroded surfaces was examined by using scanning electron microscopy (SEM). Possible erosion mechanisms were discussed.

Keywords: Particle erosion; Polymer matrix composite; Scanning electron microscopy; Surface morphology

1. Introduction

Polymer composites that were reinforced by unidirectional or short fibres possess usually very high stiffness and strength. Therefore, such composites are frequently used in engineering parts in automobile, aerospace, marine and energetic applications which could be subjected to solid particle erosion [1]. Due to the operational requirements in dusty environments, the erosion characteristics of the polymeric composites may be of high relevance. Erosion tests have been performed under various experimental conditions (erosive particle speed, characteristics, etc.) on different target composites. As known, polymer composite materials exhibit poor erosion resistance as compared to metallic materials [1]. It is also known that the erosive wear of polymer composites is usually higher than that of the un-reinforced polymer matrix [2]. It has been concluded that composite materials present a rather poor erosion resistance [3]. Fibre reinforcement does not enhance the wear performance of polymers in every wear mode. In many cases, it worsens the performance of a neat polymer [4].

The effects of the most important factors influencing the erosion rate of materials are the impact velocity, impact angle of the erodent particles, the size, shape and hardness of eroding particles [5]. In the erosion tests, polymers show ductile nature, and it is known that [6,7] ductile materials have a peak erosion rate around 30° since cutting mechanism is dominant in erosion [6,7]. Glass fibres are a typical brittle material, so that erosion is mainly caused by damage mechanisms as micro-cracking or plastic deformation due to the impact of particle. In a brittle manner, damage is supposed to increase with the increase of kinetic energy loss. According to Hutchings et al. [8], kinetic energy loss is maximum at an impingement angle of 90°, where erosion rates are maximum for brittle materials.

Especially in unidirectional fibre reinforced polymers, there is a strong relation between the particle impingement angle and fibre directions. Under parallel impact, matrix material is easily removed, the particles hit the fibre directly and thus the interface between fibre and matrix becomes

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less dominant. On the other hand, in the case of perpendicular impact, the resistance to the lateral component of bending moment is lower and bundles of fibres get bent and broken more easily.

In random oriented short fibre reinforced polymer composites, there is an interesting morphology, which affects the erosive wear performance of material. Composite material contains a mixture of ductile (polymer) and brittle (short fibre) components. On the other hand, there is a random fibre orientation with respect to the impingement direction (parallel, perpendicular or angular) of the particle which gives a complicate wear morphology.

Polyphenylenesulphide (PPS) materials are used as coating and structural materials in applications, which work under erosive wear conditions. Therefore, study of their behaviour under erosive wear conditions has an important place in machine design. However, a comprehensive and systematic study of erosion of random oriented glass fibre and calcium carbonate filled hybrid PPS composites has not previously been performed.

The objective of the present investigation is to study the solid particle erosion characteristics of random oriented glass fibre and calcium carbonate ($CaCO_3$) mineral particle reinforced hybrid PPS composites under various experimental conditions.

2. Experimental

PPS composites used in this study were kindly supplied from Ticona-GERMANY as injection moulded 80 × 80 mm plaques with a thickness of 2 mm. PPS matrix was reinforced by random oriented short glass fibre (40% w/w) and $CaCO_3$mineral particulate (25% w/w) (total: 65% w/w). The commercial name of the material was 6165A4. Test samples of approximately 40 mm × 40 mm × 2 mm in dimensions were cut using a diamond cutter from injection moulded plaques. Table 1 summarizes the physical properties of the materials [9].

Before the erosive wear tests all specimens were cleaned with acetone, balanced at electronic balance with the accuracy of 0.1 mg. Great care was given to ensure clean surface before and after wear tests. Sand and dust particles were cleaned after erosion test with air blasting and then balanced carefully.

The room temperature erosion test facility used, in the present investigation, the angular silica sand particles with the size of 150–200 μm (Fig. 1) which were driven by a static pressure, P, of 4.5–1.5 bar and were accelerated along a 50 mm long nozzle of 5 mm diameter. The average velocity, (v), of the silica sand at these pressures at the nozzle tip was 60 m/s. Composite samples mounted in the specimen holder. Then mounted specimens were subjected to a particle flow at a given impingement angle between 15° and 90°. Erodent mass flow was measured as 9, 6.25 and 4.25 g/s for 60, 40 and 20 m/s, respectively. Wear was measured by weight loss after each 15 s of erosion.

Table 1
Properties of the short glass fibre/mineral particle reinforced PPS composites

Glass transition temperature (T_g)	110 °C
Melting temperature (T_m)	280 °C
Tensile strength	130 MPa
Tensile modulus	19,000 MPa
Flexural modulus	18,800 MPa
Flexural strength	210 MPa
Compressive strength	230 MPa
Compressive modulus	18,500 MPa
Impact strength Charpy	20 kJ/m^2
Rockwell hardness (Scale M)	100
Density (g/cm^3)	1.95

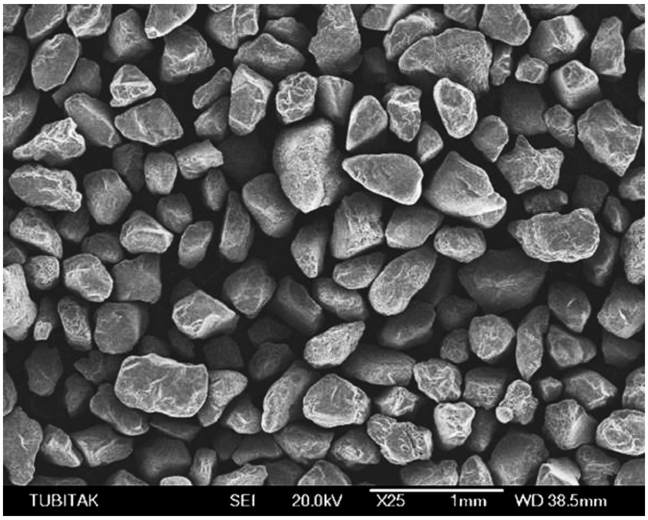

Fig. 1. The angular silica sand particles.

To characterise the morphology of the eroded surfaces and to understand the mechanism of material removal, the eroded samples were observed using a scanning electron microscope (JOEL JSM-6335F field emission scanning electron microscope). The samples were gold sputtered in order to reduce charging of the surface.

3. Results and discussions

Fig. 2 illustrates the weight loss of PPS composite as a function of erosion time at different impingement angles. The curve shows taht a steady state is reached, in which weight loss is proportional to the erosion time that has impacted on the specimen in the form of brittle materials as indicated in Refs. [6,7]. Although lower impingement angles (15° and 30°) tend to result in ductile interaction, no incubation period was observed like in ductile materials. Without an incubation period for all impingement angles (from 15° to 90°) there was a linear proportion for erosion rate and erosion time.

The behaviour of ductile materials like polymers is characterised by maximum erosion rate at low impingement angles (15°–30°). Brittle materials, on the other hand, show maximum erosion under normal impingement angle (90°). Reinforced composites have been shown, however, to exhibit a semi-ductile behaviour with maximum erosion occurring in the angular range 45–60° [10].

Fig. 3 shows the variation of the normalised erosion rates as a function of impingement angles for three different particle speeds. Erosion rates were calculated by dividing the weight loss of specimen by the mass of erodent that impacted. The influence of impingement angle and impact velocity on the erosion rate of short GF and particulate reinforced PPS. The erosion rate is maximum at an impingement angle of 60° (Fig. 3). This is semi-ductile ero-

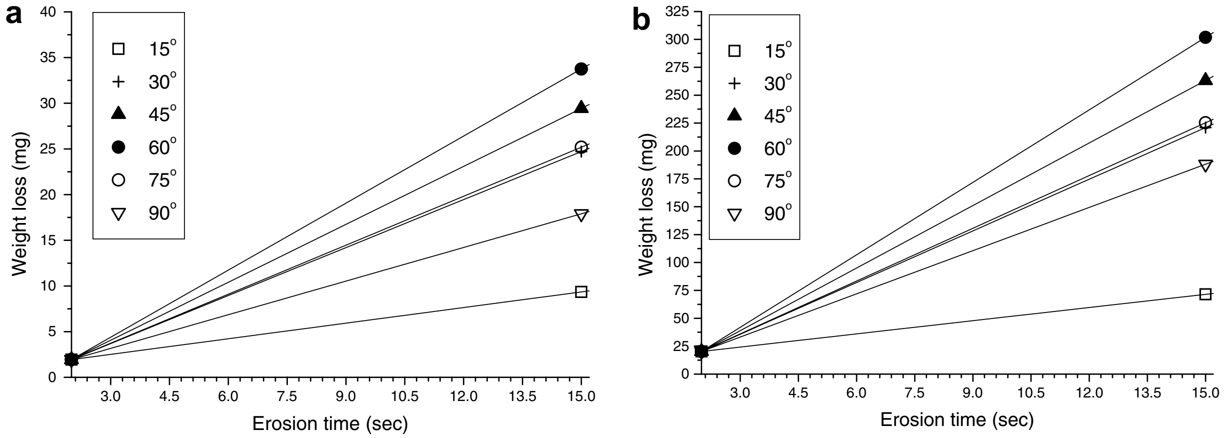

Fig. 2. The weight loss of PPS composite as a function of erosion time at different impingement angles. (a) $v = 20$ m/s, (b) $v = 60$ m/s.

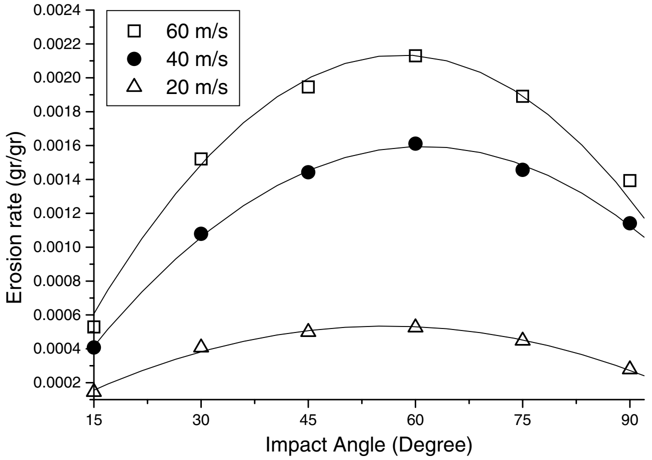

Fig. 3. Normalised erosion rate as a function of impingement angles for different particle speeds.

sion behaviour. The erosion rate was increased with increase in impact velocity up to 60 m/s. Maximum erosion rate at 60 m/s is approximately 1.3 times higher than erosion of 40 m/s, and 4.2 times higher than erosion of 20 m/s.

A possible reason for the semi-ductile erosion behaviour in the present study is that the brittle short glass fibres used as reinforcement for the PPS matrix are a typical ductile material. The erosion of fibre is mainly caused by damage mechanisms as micro-cracking or plastic deformation due to the impact of silica sand. Such damage is supposed to increase with the increase of kinetic energy loss. According to Hutchings et al. [8], kinetic energy loss is maximum at an impingement angle of 90°, where erosion rates are maximum for brittle materials. In the present study also, the peak erosion rate occurs around an impingement angle of 60° due to the semi-brittle nature of PPS composites.

Scanning electron microscopy (SEM) micrographs of original (untested) sample surface are shown in Fig. 4. It is possible to see the flat surface without having craters and scratches. Several random oriented fibres and $CaCO_3$ particles which are located nearby the surface can be seen in Fig. 4.

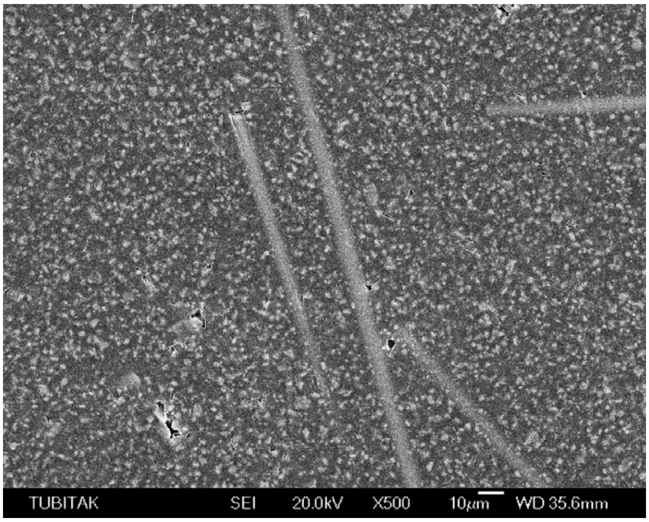

Fig. 4. SEM micrographs of original (untested) sample surface.

In general, thermoplastic matrix composites exhibit a ductile erosive wear (plastic deformation, ploughing, and ductile tearing), while thermosetting matrix composites erode in a brittle manner (generation and propagation of surface lateral cracks). However, this failure classification is not definitive because the erosion behaviour of composites depends strongly on the experimental conditions and the composition of the target material. It is well known that impingement angle is one of the most important parameters in erosion behaviour. It is reported in the literature that when the erosive particles hit the target at low angles, the impact force can be divided into two constituents: one parallel (F_p) to the surface of the material and the other vertical (F_v). F_p controls the abrasive and F_v is responsible for the impact phenomenon. As the impact angle shifts towards 90°, the effects of F_v become marginal. It is obvious that in the case of normal erosion all available energy is dissipated by impact and micro cracking, while at oblique angles due to the decisive role of the F_v the damage occurs by micro-cutting and micro-ploughing. Earlier investigators have also observed anisotropy of erosion behaviour in reinforced composites [1].

Fig. 5 shows micrographs of surfaces eroded at an impingement angle of 15° and an impact velocity of 20 and 60 m/s. When impacting at low angles, the hard erodent particles can penetrate the surfaces of the samples and cause material removal by micro-cutting and micro-ploughing (Fig. 5). It is possible to investigate the particle flow direction easily from the wear trace of the particles, which are indicated by arrows in the micrographs. As explained above in lower impingement angles, erosive wear happened dominantly in abrasive mode. The higher particle speed of 60 m/s (Fig. 5b) makes the sample surface remarkably rougher compared to the lower particle speed of 20 m/s (Fig. 5a).

There is no meaning in indicating the erosion direction with random oriented short glass fibre, as the fibres are randomly distributed in the composite. This is due to the fact that in cases of short glass fibre and mineral particle-reinforcement, the probability that an erodent particle hits a fibre in parallel direction is rather less compared to the probability that the particle impacts the fibre oblique. For this reason, it is expected that perpendicular impact morphology will be dominant for the samples.

Under parallel erosion, the matrix is uniformly grooved and cratered with local material removal (Fig. 6). Between the fibres which are parallel aligned, the deformation of the matrix material is characterised by ductile flow of the material around the impact site, therefore a ploughing mechanism is encountered. The parallel component of the impact force can make the erodent particles to penetrate into the eroded surface.

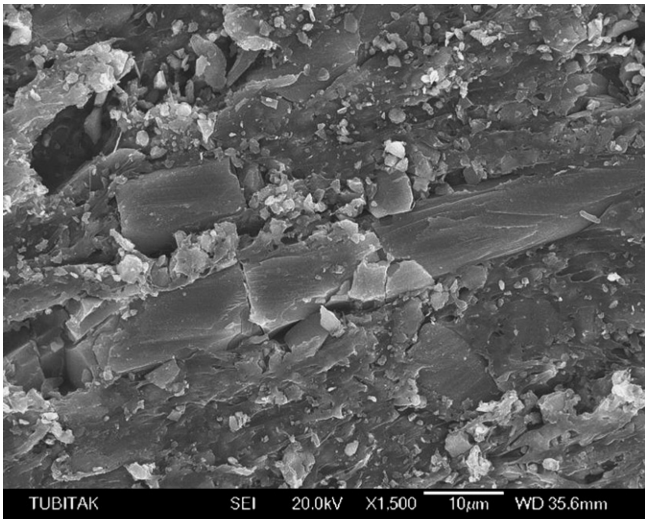

Fig. 6. SEM micrograph of eroded surface: Parallel impact of fibre at an impingement angle of 15° ($v = 20$ m/s).

Under parallel impact, when the matrix material is removed, the sand particles hit the fibre directly and thus the interface between the fibre and the matrix becomes less dominant. Fig. 6 shows a portion of the eroded surfaces with fibres parallel to the direction of silica sand impact. The matrix covering the fibre seems to be chipped off and the crater thus formed shows an array of almost intact fibres. In the case of parallel erosion, bending of fibres associated with indentation is limited. There is a local removal of matrix material from the impact surfaces resulting in exposure of fibres to the erosive environment. The fibres are still held firmly in place as yet by the undamaged matrix material surrounding them [3]. In the case of parallel erosion, the many broken fibre fragments are mixed with the matrix micro flake debris. It is also seen that the fibres protruded out of the matrix phase. The damage was characterised by separation and detachment of broken fibres from the matrix.

It is seen from the micrograph that transverse particle flow creates bending of fibres, fibre cracking and subse-

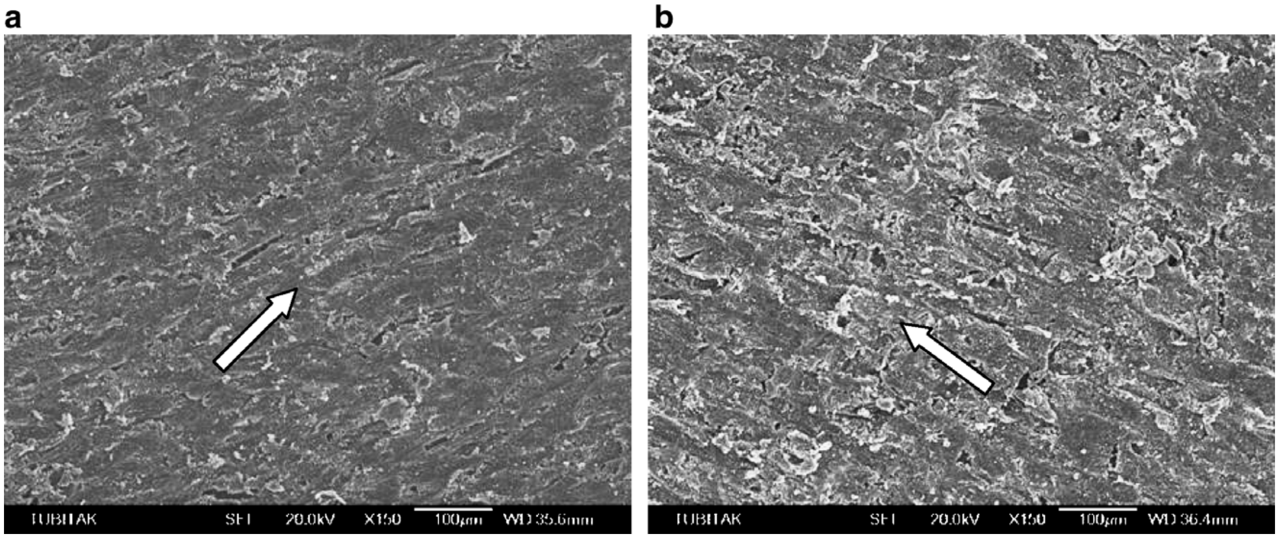

Fig. 5. SEM micrographs of surfaces eroded at an impingement angle of 15°. (a) 20 m/s, (b) 60 m/s.

quent fibre removal (Fig. 7). One of the bent fibres is broken but not removed due to its good adhesion. In the case of perpendicular impact, the resistance to the lateral component of bending moment is lower and fibres bend and break more easily. The micrographs show that one bent glass fibre is embedded in a plastically deformed matrix (Fig. 7). The impact of silica sand particles on the fibres causes the fibres to break owing to the formation of cracks perpendicular to their length. It is seen from the micrograph that transverse particle flow creates bending of fibres, fibre cracking and subsequent fibre removal.

The ductile flow and the penetration of the erodent in the matrix are hampered by fibres aligned in Pe-direction; therefore, the grooves were far less intense and obviously less material was removed in this case [3]. The fibres in anti parallel direction get micro cracked and micro cut very easily as compared to the parallel fibres.

Impingement angle of 60° was the maximum angle which results in maximum particle erosion. Very rough surfaces are investigated in Fig. 8a and b. Particles with a higher kinetic energy at 60 m/s make the sample surface rougher (Fig. 8b) compared to lower speed (Fig. 8a).

Fig. 9 shows micrographs of surfaces eroded at an impingement angle of 60°. Repeated impact of the erodent caused roughening of the surface of the material. A characteristic feature of more cutting with chip formation is reflected. Erosion along the fibres and clean removal of the matrix to expose glass fibres is also seen. The matrix was strictly plastically deformed. The matrix shows multiple fractures and material removal. The exposed fibres

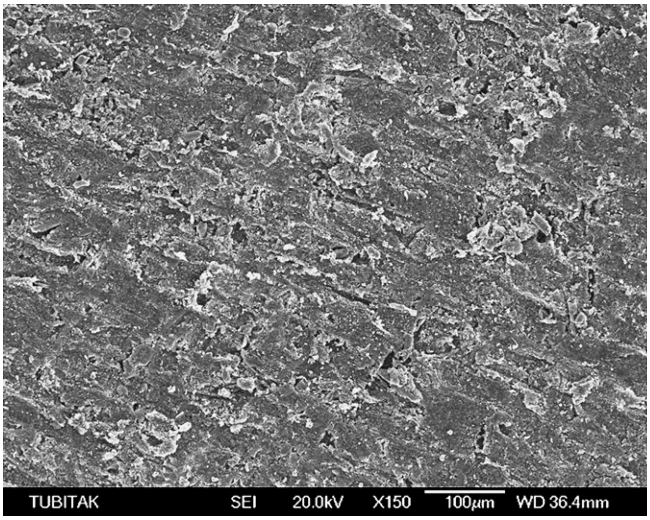

Fig. 7. SEM micrograph of eroded surface: Perpendicular impact of fibre at an impingement angle of 15° ($v = 20$ m/s).

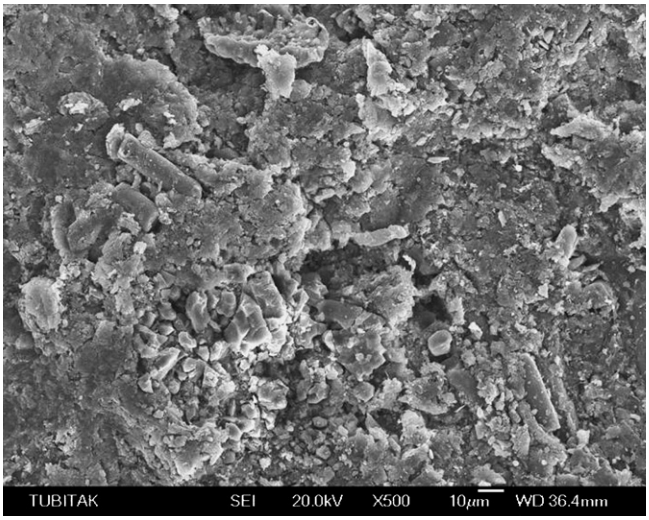

Fig. 9. SEM micrograph of eroded surface at an impingement angle of 60° ($v = 60$ m/s).

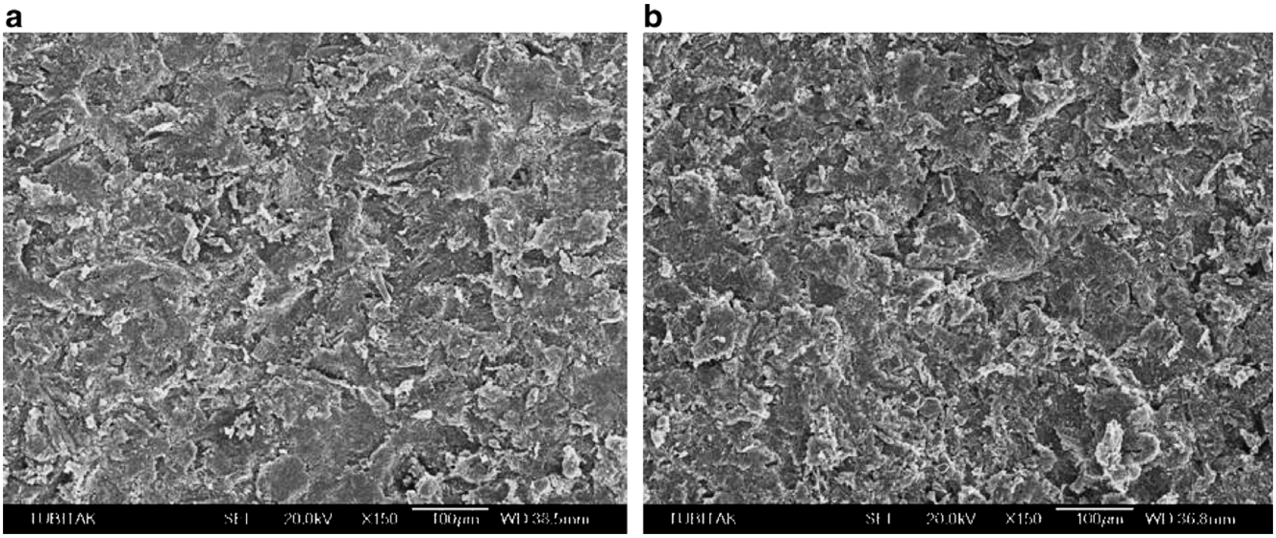

Fig. 8. SEM micrograph of eroded surface at an impingement angle of 60°. (a) $v = 20$ m/s, (b) $v = 60$ m/s.

are broken into fragments and thus can be easily removed from the worn surfaces. Also some of the bent glass fibres embedded in plastically deformed matrix. Localised pit formation was also apparent on the surface. At 60° both abrasive deformation (micro ploughing, micro cutting, etc.) and impact deformation mechanism were observed. Naturally an angle of 60° is closer to the normal, that is why the impact behaviour of the particle is more dominant compared to the abrasive behaviour.

Particle impingement transfers its kinetic energy to the samples. As seen in Fig. 10, this energy results in elastic and plastic deformations. It may produce high temperature on the surface which makes the deformations easy. In Fig. 10 a remarkable matrix deformation is clearly seen. The high temperature known to occur in solid particle erosion [1] could soften the matrix. In the present study also melt flow of the matrix can be clearly seen in the micrograph (Fig. 10).

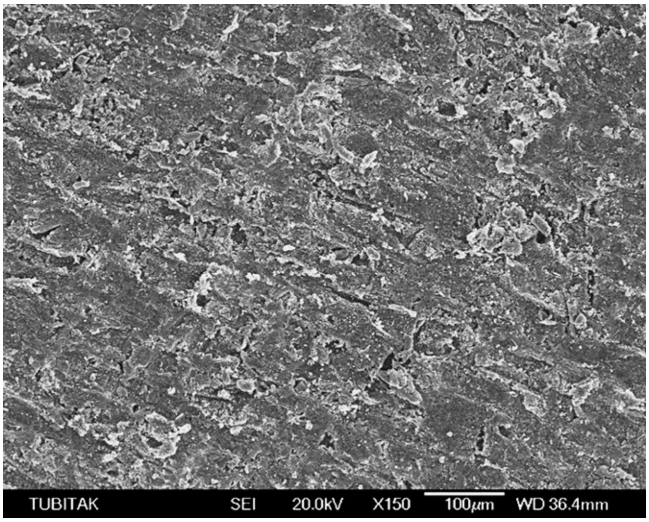

Fig. 10. SEM micrograph of eroded surface at higher magnification an impingement angle of 60° ($v = 60$ m/s).

Normal erosion occurs at an impingement angle of 90°. SEM micrographs of surfaces eroded at an impingement angle of 90° were seen in Fig. 11. At normal erosion a great impingement occurred which plastically deformed the sample surface remarkably. But this impingement did not result in a higher wear loss as in the case of brittle materials. Because at this obtuse angle particles were caused the compressive pressure at the surface. This pressure resulted in crater formation, but there was no material loss in this process. Also these plastically deformed layers possibly have higher mechanical properties with a greater hardness. Fig. 11b represents the erosion which took place at a particle speed of 60 m/s and it is possible to observe those highly plastically deformed zones compared to Fig. 11a, which represents the erosion that had occurred at a particle speed of 20 m/s.

Fig. 12 shows micrographs of surfaces eroded at an impingement angle of 90° and an impact velocity of 60 m/s. It is obvious that during normal erosion, all the available energy was dissipated by impact. There are no micro ploughing and micro cutting mechanisms that occurred in normal erosion. Hence angular sand particles penetrate very easily into the soft polymer matrix or cause plastic deformation and numerous crater formations in the matrix The continuous impact of sand particles on the composite surface resulted in local removal of matrix and hence fibres protruded out of the matrix phase (Fig. 12).

Also Fig. 12 shows embedded fractured sand particles (as a result of impingement) of size approximately 5 × 5 μm, which impact at 90°. These embedded sand particles are indicated with an arrow. To make sure of the material, EDX analysis was done on this embedded particle and we realized that this particle is a piece of silica sand particle.

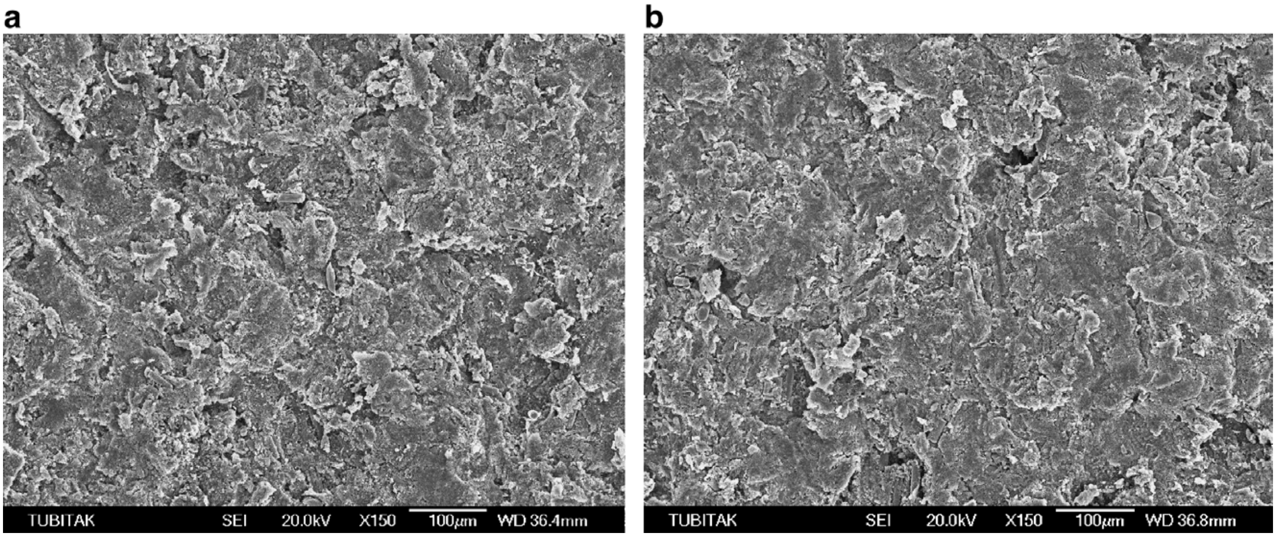

Fig. 11. SEM micrograph of eroded surface at an impingement angle of 90°. (a) $v = 20$ m/s, (b) $v = 60$ m/s.

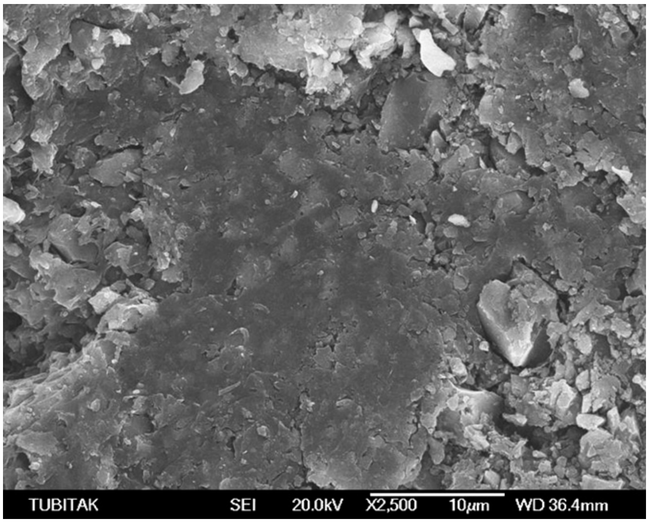

Fig. 12. SEM micrograph of eroded surface at an impingement angle of 90° ($v = 20$ m/s).

4. Conclusions

Based on this study of the solid particle erosion of random oriented short glass fibre and mineral particle ($CaCO_3$) composites at various impingement angles and impact velocities, the following conclusions can be drawn:

1. The peak erosion rate shifts to a larger value of impingement angle compared to the ductile materials and due to the brittle nature of the glass fibre and particle reinforcement the composites exhibited a maximum erosion rate at an impingement angle of 60° under the present experimental condition for three different particle speeds.
2. Impingement angle of the particles is one of the important parameter that strictly affects the erosive wear characteristics of the material. The material wear mechanisms are in close relationship with the impingement angles.
3. Because of PPS matrix reinforced by random oriented short glass fibres, it is not possible to investigate the fibre orientation effects on the wear mechanisms. But statistically the perpendicular impact has a higher possibility compared to parallel impact. This is why we have investigated that perpendicular impact type morphologies are a dominant wear mechanism.
4. We have not observed any additional effects of mineral particle on erosion wear resistance of the material during the investigation of SEM studies. But we believe that the mineral particles have a positive role on erosive wear resistance of the material as a result of increasing the total hardness, modulus and mechanical properties of the materials.
5. The morphologies of eroded surfaces observed by SEM suggest that the overall erosion damage of composites consists of matrix removal and exposure of fibres, fibre cracking and removal of broken fibres.

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