FE simulation of the indentation deformation of SiC modified vinylester composites in respect to their abrasive wear performance

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Abstract. The abrasive sliding friction and wear behaviours of silicon carbide (SiC) filled vinylester (VE) composites were investigated. The average grain size of the incorporated SiC particles was varied, holding the volume content of them in every case at 16 vol%. Mechanical properties (hardness, compression modulus, yield stress) of the filled and neat VE were determined. The tribological properties were investigated in block (composite) – on – ring (steel) test configuration. The steel counter bodies were covered with abrasive papers of different graining. Coefficient of friction (COF) and specific wear rate of the VE + SiC composites were determined. It was observed that the wear resistance increases with increasing average filler grain size and with decreasing abrasiveness of the counter surface. The COF of the VE + SiC composites is independent of the size of the incorporated particles, but it is strongly influenced by the abrasiveness of the counter body. The worn surfaces of the VE + SiC systems were analysed in scanning electron microscope (SEM) to deduce the typical wear mechanisms. The size effect of the SiC filler particles onto the abrasive wear characteristics was investigated by assuming that the roughness peaks of the abrasive paper and the indenter of the microhardness test cause similar micro scaled contact deformations in the composites. Therefore FE method was used to simulate the micro scaled deformation process in the VE + SiC systems during microindentation tests. The FE results provided valuable information on how to explain the size effect of the incorporated SiC filler.

Keywords: polymer composites, reinforcements, thermosetting resins, modelling and simulation, abrasive wear

1. Introduction

For metallic materials a suitable correlation exists between the wear behaviour and the hardness. For polymeric materials such a general usable dependence wasn't found yet. Though some correlations between the wear performance and material properties were already prepared, they are valid always only for special materials and circumstances [1–3]. Especially under abrasive conditions the micro scaled deformation behaviour plays an important

role in the wear process, because of the occurring mechanisms like 'micro ploughing' and 'micro cutting'.

Tribotechnical systems are characterised by an interplay between contacting surfaces which are in relative motion to one other. If the surfaces are not separated by a lubricating film (for example sufficient lubricant is not available or its viscosity is too low to produce an appropriate lubricating film thickness) the surfaces are in direct contact. The

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Figure 1. Two body contact (left) and three body contact (right) by abrasive wear process [7]

consequence is the onset of wear. If the counter body is harder and rougher than the base material abrasive wear occurs. The presence of hard particles in the contact area between two surfaces also leads to abrasive wear. Accordingly, the abrasive wear processes can be grouped into two-body and three-body contact ones (see Figure 1) [4, 5].

Abrasive wear events cover different material separation processes listed below. In ductile materials furrows result in chip formation, the related process is called micro cutting. The rising edges of the furrow, caused by surface deformation, are formed by micro plowing (see Figure 2). The relationship between the two processes – micro cutting and micro plowing – is affected also by the inclination angle of the abrasive counter part. In brittle materials beside the edges of the furrow additional cracking and crack growth take place (micro cutting). With multiple furrowing it comes to micro fatigue phenomena [4, 6].

In the case of single path sliding under abrasive conditions the wear rate of pure polymer materials is usually smaller than that of filled composites. However, this behaviour changes with increasing repetitions (multipath sliding), and the composite materials are often better than the neat ones concerning the wear after an initial phase. On the one

hand this can be attributed to the formation of a protecting boundary layer between the sliding pairs. The polymer-based boundary layer triggers an adhesion dominated tribological process. On the other hand filler and reinforcement materials are added to improve the wear characteristics, for example internal lubricants such as poly(tetrafluoroethylene) (PTFE) or graphite. Note that filler and reinforcement materials may lower the cohesive forces (binding forces) within the composite. This supports furrowing, tearing and cutting processes. Furthermore, the fillers may act as stress concentrators and the consequence may be prominent cracking and fatigue in the corresponding composite material [8–11].

The question arises, how the incorporation of fillers and reinforcements influence the abrasive wear? With the addition of reinforcement materials, like ceramic particles, the wear characteristics under abrasive conditions can be improved, whereby the particle size seems to play an important role [12–14]. To sum up, it can be concluded that the micro scaled deformation behaviour of reinforced composites plays a crucial role in respect to abrasive wear. Penetration conditions of the abrasive particles and/or roughness peaks of the counter bodies (contact angle and load type) are likewise crucial.

The working hypothesis of this study was that there is a correlation between the micro scaled deformation of polymer composites, accessed by micro hardness (Martens hardness) and their abrasive wear behaviour. It was also supposed, that finite element (FE) simulation is the right tool to understand the penetration process of the indenter during Martens tests [15]. The simulation of a dynamic microhardness test for vinylester based composite materials, reinforced with silicon carbide particles, offers the possibility to determine the influence of the particle reinforcement on the micro scaled deformation behaviour of the matrix material. With the results of the FE simulation the opportunity is

Figure 2. Presentation of both material detachment processes 'micro cutting' and 'micro plowing' [7]

given to draw conclusions about the wear behaviour under abrasive conditions.

2. Materials and material production

For the modification of the base vinylester (VE) resin silicon-carbide (SiC) was selected as reinforcement material. With the help of the SiC particles both the material stiffness, especially the compression strength, and wear characteristics under abrasive conditions were to be improved. In order to consider the influence of the particle size, SiC particles with a middle grain size of 3 and 9 µm, respectively, were used. Moreover a composite material was produced, which contained SiC particles in both sizes (3 and 9 µm). In each case 16 vol% SiC were incorporated into the VE matrix. Further on these materials will be referred as material A (pure VE resin), material B (VE + 16 vol% SiC (3 µm)), material C (VE + 8 vol% SiC (3 µm) + 8 vol% SiC (9 µm)) and material D (VE + 16 vol% SiC (9 µm)). The exact material compositions are summarized in Table 1.

For the production of the VE composites a laboratory dissolver was used (Dispermat AE3-M, VMA Getzmann GmbH). The used VE (Synthopan UPM, Synthopol Chemistry) contained styrene as crosslinking agent. The styrene content of the VE was 25 vol%. Methyl ethyl ketone based peroxide served as initiator. To crosslink the resin already at ambient temperature, Oldopal 64 (Büfa Reaktionsmittel) accelerator was used, which is based on cobalt and dimethyl aniline. The so called cold crosslinking has the advantage that the sedimentation of relatively large and heavy filler materials can be prevented because the resin begins to gel promptly.

After the mixing process, the materials were poured in forms (dimensions: 100×100×10 mm³) and hardened at ambient temperature. In order to harden the samples completely, they were transferred into a

furnace and kept for 60 minutes at 120°C. Specimens for material characterisation were prepared from these plates.

3. Experimental

3.1. Mechanical properties

In order to be able to simulate the deformation behaviour of the materials, it is necessary to know the elastic modulus (material stiffness) and the yield stress (load where that the plastic deformation begins) of the matrix material under compression. The related tests were accomplished on the pure VE resin (matrix) in accordance with the DIN 604 standard, using an universal test equipment (1474 Zwick, Ulm, Germany). The results are summarized in Table 2.

3.2. Density measurement

The density of the composites was measured using the Archimedes principle (buoyancy method with water) according to the ISO 1183 standard. The density measurements were done at a Mettler AT261 (Giessen, Germany) micro balance.

3.3. Microhardness tests

Microhardness tests were carried out on all materials using a dynamic ultra microhardness testing set (Shimadzu – type DUH 202) following the DIN 50359-1 norm. The measurements were performed at two different maximum loads, 100 and 1500 mN respectively. On each material 10 measurements were made with a test speed of 70 mN/sec. The universal hardness values (*HU*) were derived from the measured penetration force *F* [N] and penetration depth *h* [mm] values in accordance with Equation (1):

$$HU = \frac{F}{26.43 \cdot h^2} \quad [\text{MPa}] \quad (1)$$

3.4. Abrasive wear tests

The tribological behaviour of the composites was determined in block-on-ring abrasion tests. This set-up was selected because there is a good analogy between it and the sliding bearings contact situation

Table 1. Material compositions of the vinylester-based composites

Material name	Basis-polymer	SiC content (middle grain size)
A	VE	0 vol% (pure resin)
B	VE	16 vol% SiC (3 µm)
C	VE	8 vol% SiC (3 µm) + 8 vol% SiC (9 µm)
D	VE	16 vol% SiC (9 µm)

Figure 3. Sketch of the block on ring testing method (left) and a photograph of the set-up (right)

(geometry and movement type). In order to study effects of the abrasive contact conditions, tribotests were run against different abrasive counter bodies. For this, the steel counter bodies were covered with abrasive paper of different graining. The designations of the three applied abrasive papers were: 240 (middle grain size approx. 42–46 μm), 320 (middle grain size approx. 27–30 μm) and 400 (middle grain size approx. 16–18 μm). These abrasive papers will be referred further as abrasive paper 240, 320 and 400, respectively. In Figure 3 both the test principle and the set-up are displayed.

In all tribotests the following parameters were used: surface pressure p : 0.5 MPa, running speed v : 0.32 m/s, testing period t : 60 s.

The experimentally determined results of the abrasion tests are based on the determination of the mass loss over the time. Therefore each sample was weighed before and after the test and from the weight difference the specific wear rate (w_s) was calculated in accordance with Equation (2):

$$w_s = \frac{\Delta m}{L \cdot \rho \cdot F_N} \quad [\text{mm}^3/\text{N} \cdot \text{m}] \quad (2)$$

where Δm [g] denotes the mass loss of the test specimen, L [m] is the glide path of the sample on the counter body, ρ [g/mm³] is the density of the test specimen and F_N [N] is the normal force.

3.5. Wear mechanisms

For examination and qualitative description of the wear mechanisms the surfaces of the tested samples were investigated in scanning electron microscope, (SEM; JSM5400 of Jeol, Tokyo, Japan). Prior to SEM inspections the samples were coated with Au/Pd layer with a sputter machine of Balzers (Lichtenstein).

4. Results of the mechanical and wear tests

4.1. Compression properties

The compression modulus of the vinylester (VE) was determined as the tangent of the initial linear range of the compression stress-strain curve. The yield point is defined as that compression stress where the plastic deformation begins. The compression modulus of the SiC particles was given by the manufacturer.

Table 2. Material parameters, which are used for the simulation

Property/ material	E-modulus [GPa]	Yield stress [MPa]	Grain size [μm]
VE	3.2	132	–
SiC	455	–	3 and 9

4.2. Universal (Martens) hardness values

The computed universal hardness values are depicted in Figure 4. The pure VE resin exhibits a lower universal hardness compared to the SiC modified composite materials, as expected. Furthermore, it can be seen that the universal hardness values with lower test load (100 mN) are higher than with higher ones (1500 mN). It can be traced to the fact that with decreasing test load the relationship between elastic and plastic deformation changes [16]. This means that with the lower test load, the Vickers indenter does not penetrate so deeply into the material, and the rather elastic deformations are strongly influenced by the SiC particles. Therefore the measured values at lower loading exhibit also a higher scatter compared to those measured at high loading. With a higher test load the Vickers indenter penetrates more deeply

Figure 4. Universal hardness values of the materials

into the material and an integral value for the hardness is determined, which is less influenced by local differences in the material. When higher test load was applied the scatter range was reduced and the measured universal hardness values were very similar to one another for the three different composites. It is recognizable that the two composite materials – B and C – exhibit the same universal hardness (at 100 mN test load). However a lower average universal hardness value was determined for the composite material D.

4.3. Specific wear rates

In Figure 5 the specific wear rates are represented as a function of the SiC particle size for the three abrasive papers of different graining. As expected, the pure VE resin under these test conditions exhibits very high wear rates hence these were not considered in the representation. The wear rate of the pure VE resin was at about $0.5 \text{ mm}^3/\text{Nm}$ against abrasive paper 320.

Figure 5 shows that the specific wear rate decreases when the grain size of the used abrasive paper decreases. It means that the wear also decreases with sinking abrasiveness of the counter body. The composite material, which contains only $3 \mu\text{m}$ SiC particles shows under all three conditions the highest wear rates. Interestingly the same specific wear rate was found in the tests run against the two abrasive papers 320 and 400. So it can be concluded that the reduction of abrasiveness between these two graining does not affect any more positively the wear characteristics.

On the other hand the two materials C and D show permanently decreasing wear rates with decreasing

abrasiveness of the counter body. Against the roughest abrasive paper 240 the material C shows higher wear values than material D. In case of materials C and D the wear rate values practically coincide with decreasing abrasiveness of the counter body (cf. results against the abrasive paper 400 in Figure 5). The reason of this phenomenon is that the smaller particles ($3 \mu\text{m}$) can be more easily broken out if the abrasiveness of the counter body is high enough.

4.4. Coefficient of friction

During the wear tests the arising friction forces were detected. From this the coefficients of friction (referred further as COF) can be determined as a quotient of the measured friction forces and the applied normal force. The duration of tests was 60 seconds. During the tests first an initial transient tribological process was observed. Due to this the average COF values were determined from the values of the second half of the tests (from $t = 30$ to $t = 60$ seconds), see Figure 6. The COF values of material A aren't considered in the representation. The COF value of material A against abrasive paper 320 was about 0.7.

Figure 6 shows that the three materials (B, C and D) have almost the same COF values independently from the contained grain size of the SiC (at the same abrasiveness of the counter body). Moreover it can be clearly seen that the COF values increase versus the decreasing abrasiveness of the counter body. The rough abrasive paper and the composite glide more easily on each other because the large abrasive particles have small real contact

Figure 5. Specific wear rates of the different composites

Figure 6. Detected coefficients of friction (COF) values (average values of the last 30 seconds of the tests)

area in the process zone. The real contact area increases with decreasing grain size of the abrasive paper. This causes a more intensive contact between the counter body and the composite material and thus the COF increases. Fact is that the size ratio of the particles in the abrasive paper and in the composites becomes even smaller with decreasing abrasiveness. Due to this the probability of collisions of filler and abrasive particles increases, causing higher COF. This phenomenon is especially dominant for material D.

4.5. Wear mechanisms

The worn surfaces of the samples were analysed with a scanning electron microscope. In Figure 7 one can see the surfaces of the samples, tested against the abrasive paper 240. The wear track caused by the most abrasive paper was analysed, as

this yielded to the most prominent wear. The arrow in Figure 7 indicates the sliding direction of the counter body.

The abrasive wear (furrowing and scratching) can be well resolved even at low magnifications (pictures on the left side) in all materials. Material B exhibits strongly fractured surface (cf. Figure 7a). One can observe heavy damages with many small, but relatively broad cracks in the wear track (cf. Figures 7b and 7c). Note that not only the surface, but also the base material under the contact surface was damaged. Due to the severe wear, the surface is covered with wear particles.

At the lowest magnification one can see that material C exhibits a less destructed surface than material B (cf. Figure 7e). Also the other two magnifications of the wear path show fewer damages and cracks (cf. Figures 7f and 7g). The cracking is moderate with some subsurface damage in the material.

Figure 7. Scanning electron microscopy pictures about the wear tracks of the different composites, material B (a, b and c), material C (e, f and g) and material D (h, i and j). Note: The counter body was in all cases abrasive paper 240 with an average grain size of 42–46 μm .

Wear debris are less on the surface of C than of material B.

The last composite, material D (cf. Figure 7h) suffered obviously the lowest damage and wear during the tribotests. The smallest enlargement shows a raw surface without deep scratching or furrowing. The two other SEM pictures (cf. Figures 7i and 7j) confirm a moderately damaged surface structure. The cracks on the surface seem to be relatively short which are likely not deeply penetrating below the surface.

The universal hardness values of the investigated materials provide no interpretation related to the effect of the filler particle size on the wear characteristics. Therefore we need to find another way to elucidate the mentioned size effect of the filler particles.

We assume that the abrasive roughness peaks and the microindenter should cause similar deformations in the composites, in spite of that the average penetration depth of the abrasive particles and the penetration depth during the microhardness tests are probably different. Therefore to shed light on the size effect of the SiC particles the FE method will be adopted to simulate the stress and strain behaviour of the different composites during microindentation tests.

The micro scaled strain and stress distributions calculated by FE should be in correlation with the observed wear performance of the different composites.

5. Simulation of the micro scaled stress and strain behavior

The Cosmos/M Geostar FE software was used to simulate the micro scaled deformation process during microindentation tests. Microhardness tests with a maximum load of 100 mN were FE modelled. The microhardness tests were carried out using a Vickers diamond indenter. The Vickers indenter is pyramid shaped with a plane angle of 136° . Due to the symmetrical shape of the indenter, one can assume that the loads are distributed equally at all four sides the diamond pyramid during the tests. This assumption makes it possible to reduce the simulation to a quarter model (see Figure 8). Thus the available nodes (approx. 60 000) can be placed denser below the indenter.

The quarter models of the simulations correspond in all three cases to a volume of $200 \times 200 \times 200 \mu\text{m}^3$. The models contain in each case 50907 nodes and 59357 elements (Solid elements with 8 nodes). The models are micro models, where the reinforcement particles (SiC) are embedded in the matrix (VE). Both the VE matrix and the SiC particles exhibit their own specific material properties. The material law of the VE matrix is nonlinear. The characteristic values of the materials are summarized in Table 2.

Because the models are built up from cubes of an edge length of $2 \mu\text{m}$, the $3 \mu\text{m}$ SiC particles were implemented as cubes with an edge length of $4 \mu\text{m}$. The $9 \mu\text{m}$ SiC particles were modelled as cubes of an edge length of $10 \mu\text{m}$. The implementation of the fillers as cubes is probably right, because the SiC particles are of irregular form with sharp edges. A further assumption is that the SiC particles are present homogeneously in the matrix in macro scale, but nevertheless statistically distributed in micro scale. This statistical distribution of the different sized particles is to see in Figure 8, where the FE meshes of the three different materials (B, C and D) are displayed. The SiC particles do not exhibit strictly given structure, but an irregular statistical distribution. Further on we assumed that the SiC particles have perfect adhesion with the matrix. The penetration of the Vickers indenter into the material will be simulated using the considerations listed above. The influence of the SiC particles being present regarding the resulting stresses (von Mises stress) and strains (equivalent strains) will be calculated and demonstrated. The goal is to clarify the influence of the reinforcement particle size onto the micro scaled deformation behaviour of the matrix. Furthermore to find correlation between the FE calculated stress and strain distributions and between the wear characteristics of the different composites.

By the FE simulations the surface points of the perfectly rigid Vickers indenter were fixed. These fixed points were linked to the surface of the composite materials by contact elements. The non-linear FE calculations were force controlled. The driver force was introduced at the bottom of the quarter models, where a rigid plate was glued to the quarter model (see Figure 8). In the symmetry planes of the quarter models the proper boundary

Figure 8. FE meshes for the simulations (VE matrix always with 16 vol% SiC particles): material B (a), material C (b), material D (c)

conditions were applied and the modified Newton-Raphson method was used for the calculations [17].

6. Results of the simulations

The FE-calculated stress and strain distributions are

displayed in the Figures 9 to 13. For the better overview in the following figures the embedded SiC particles were not presented. This makes possible to visualize strain peaks and large strains (caused by the particles) in the VE matrix at the indentation zone.

Figure 9. FE-simulation results for the material A (pure VE resin)

6.1. Material A (pure VE resin)

In Figure 9 the von Mises stress and the equivalent strain distribution is displayed in the case of pure VE resin when the maximum normal load of 100 mN is applied. It can be seen that both the arising stresses and the strains concentrate immediately below the indenter. With increasing distance to the contact area, the value of the stress and strain permanently decreases. Altogether a regular stress and strain distribution can be observed in the matrix, similar to a regular Hertzian contact.

6.2. Material B (VE + 16 vol% SiC (3 μm))

Compared to the results of material A, material B shows completely different stress and strain distributions. In Figure 10 one can see that both the von Mises stress- and the equivalent strain-distributions are very strongly affected by the SiC particles in the indentation zone below the indenter. These distributions are not regular any more; they are strongly disturbed by the incorporated particles. Local stress

peaks and large strains arise in the indentation zone between the individual particles and the matrix. The location with the highest equivalent strain of 79.5% is hidden in Figure 10 therefore it is displayed in Figure 12 (left) separately. It can be concluded that the small SiC particles change their starting position due to the applied load. Because of it a strongly distorted zone with large strains will be developed at their edges in the VE matrix. The arising maximum equivalent strain is twice as high as it was in the case of the pure VE resin.

6.3. Material C (VE + 8 vol% SiC (3 μm) + 8 vol% SiC (9 μm))

In Figure 11 the simulation results of material C are represented. It can be clearly seen that both the arising stresses and strains are affected considerably by the incorporated particles. Because in Figure 11 the position of the maximum equivalent strain value is not visible, since this is at the corner of a small particle below the surface, this position is separately

Figure 10. FE-simulation results for the material B (3 μm SiC particles)

Figure 11. FE-simulation results for the material C with 3 + 9 μm SiC particles

displayed in Figure 12 (right). Observing these results, one can conclude that the matrix can be damaged quickly at the corner of the small (3 μm) particles due to the arising high stresses and strains. In this case the maximum value of the equivalent strain is 97.9%. The general impression refers to an intensely disturbed stress and strain distribution. However thanks to the larger particles (9 μm) the

stresses and strains do not extend so deeply into the material, as it was in the case of material B. The reason for it is that larger particles are embedded with a larger surface into the matrix, so their starting position can be hardly changed. Thereby the deeper regions in the matrix are protected. On the other hand in the indentation zone the small (3 μm) SiC particles cause large stresses in the matrix.

Figure 12. Sectional details of the FE-simulation results of the material B (left) and material C (right)

6.4. Material D (VE + 16 vol% SiC (9 μm))

The von Mises stress- and the equivalent strain-distributions of the material D are displayed in Figure 13. One can see that the maximum von Mises stress reaches its maximum directly underneath the indenter (see Figure 13 right above). The large SiC particles (9 μm) near to the contact zone affect considerably the distribution of the von Mises stress. However it is noticeable in this case that the stress distribution essentially concentrates below the indenter and less interaction takes place with the boundary region of the particles. The maximum equivalent strain arises likewise directly below the indenter. The SiC particles affect the strain distribution only slightly. It means that the deeper regions in the matrix are thereby protected exactly like before by the material C. From these results it can be concluded that the material failure (cracking) arises also only within a relatively small region near to the surface. One can conclude, that the large SiC particles (9 μm) affect the stress and strain distribution positively, constraining the spread of high

stresses into a relatively small volume near to the surface. One can see also that the arising maximum value of the equivalent strain is only approximately 20% higher than it was by the material A (pure VE resin).

7. Discussion of the results

The results of the wear experiments show that the difference in the SiC grain size has a relevant influence on the specific wear rates. According to this observation the FE simulations have show that the small SiC particles (3 μm) generate locally larger stresses and strains in the matrix, than the larger ones (9 μm). This can be attributed to the size ratio of the arising contact area below the indenter and the particle size within the matrix. If the size of the contact zone is comparable with the size of the reinforcement particles, then smaller stresses and strains will be developed in the matrix. The reason is that the large particles can localize the stress and strain distribution into a small volume near to the

Figure 13. FE-simulation results for the composite D material with 9 μm SiC particles

surface. In contrast to it the small SiC particles in the indentation zone will change strongly their geometrical position in the matrix due to the load of the indenter. Because of it the matrix in the environment of the small particles is strongly stressed and distorted which causes material damage. Therefore the ideal composite material for abrasive wear conditions needs to contain an appropriate size distribution of the reinforcement materials.

Further on based on the simulation results it can be explained why the specific wear values of material C and D will be nearly identical with decreasing abrasiveness. By the presence of large SiC particles the strain distribution is obstructed and the damage of the matrix below the indentation zone is moderated. Because proportionately less large particles are present in the material C, the effect of these particles comes only with decreasing abrasiveness to the fore. Finally against abrasive paper 400 the abrasiveness of the counter body becomes so small (see chapter 3.4), that the tests provide nearly identical wear values by both composite materials (C and D).

It can be noted that the experimentally determined specific wear rates and the FE simulation results show the same tendencies. The FE results were correlated also with the observed wear mechanisms of the composites, related to the density and depth of the surface cracking.

As it was mentioned before the average depth of the penetrations due to the abrasion and the penetration depth during the microhardness tests are not identical. Even so the results and the tendencies show that the above mentioned phenomenon (i.e. the size proportion of the reinforcement particles and the abrasive roughness peaks) is of basic importance.

8. Conclusions

This work has shown that there is no trivial connection between the experimentally determined universal hardness of the investigated materials and their wear performance. On the other hand the FE simulations have highlighted that the arising stress and strain distributions in the VE matrix during the microindentation process can be correlated with the abrasive wear characteristics.

FE results indicated that the size of the reinforcement particles should be comparable with that of

the roughness peaks of the abrasive paper to achieve low wear.

We can assume that the interfacial bonding strength between the matrix and the SiC particles is similar, independently from the particle size. Accordingly the resistance to change their geometrical position increases with increasing particle size. Thus larger reinforcement particles can withstand larger deformations, i.e. stronger roughness peaks, thereby protecting the base material.

Otherwise the wear resistance of a particle filled composite could be enhanced also by the improvement of the interfacial bonding strength between the particles and the matrix [18]. Further on it is necessary to note that the shape of the reinforcement particles is also extremely important in the view point of the material strength, which is influencing also the wear performance [19].

Finally we think that the following observations could refer to a connection between the universal hardness and measured COF values. It was found that the microindentation tests provide smaller universal hardness values when higher loads are applied as well as lower COF is to measure against strongly abrasive surfaces. However, this assumed correlation was not checked within this study.

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