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Research on wear resistance of poly-component composite materials

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Abstract

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The paper deals with the testing of composite materials based on corundum, silicon carbide and glass. The object of the experiments was a particle polymeric composite, whose continuous phase was in the form of a two-component epoxy resin and a discontinuous phase (reinforcing particles) of corundum, silicon carbide and glass of a specific particle size from 4.5 to 260 μm. The research was focused on the evaluation of abrasive wear resistance and hardness of the tested materials. A considerable improvement of the values obtained at measuring the abrasive wear resistance was reached at hybrid composite materials filled with three different components, when 98% improvement was reached compared to the epoxy resin without the filler. The hardness increased up to 35% by adding the filler. The particle size influenced properties of the polymeric composite as the particles of larger sizes bring a positive influence on the wear resistance and the hardness HBW 10/250/30.

Keywords: hardness; mechanical properties; polymeric composite; strength; testing, wear

Polymeric composite materials represent prospective structural materials which contain one or more discrete phases stored in a continuous phase which can be from the same or different materials (Valášek 2015). A hybrid (poly-component) composite is such material that comes into being at putting two and more types of the reinforcement into an independent matrix (Friedrich et al. 2005).

The knowledge about the diverse materials´ behaviour and their mutual interaction (namely at the composite materials) is essential to choose the optimum materials. Polymers and their composites form a very important class of tribo-engineering materials (Ravi Kumar et al. 2009). The inherent weakness of polymers could be improved successfully by using various special fillers (from micro to nano-sized particles) (Suresha, Ravi Kumar 2010). The mechanism of the filler action in reducing the wear rate of polymers has been recently a subject of an intense study (Suresha, Ravi Kumar 2010).

When applying the polymeric materials, the soil adherence to working tools and connected energy demands are minimized owing to their physical and chemical properties (Xia Jia, Ruofei Ling 2007). Xia Jia and Ruofei Ling (2007) referred that special polymeric materials are developed which are distinguished for high wear resistance.

Machines, equipment and their partial segments used in the agriculture are exposed to an intensive abrasive wear, namely in the sphere of soil cultivation (Karoonboonyanan et al. 2007). Karoonboonyanan et al. (2007) dealt with the wear resistance of plough blades with the aim to increase

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utility properties by means of various surface treatments. Regarding the wear conditions and the process intensity is an integral part of the lifetime and the reliability not only of tools, but also of the whole system (Karoonboonyanan et al. 2007; Müller et al. 2013).

The research aim of various working groups can be defined as follows: finding suitable materials and methods for the production of optimum tools whose mechanical properties would extend the tools lifetime and they would decrease the energy consumption of the soil cultivating owing to lower resistance (Müller et al. 2013). The possible solution is a creation of bimetallic tools on one hand and various additional materials on the other hand. Bonding methods are a defined problem of various materials (Müller et al. 2013). Currently, brazing and soldering are used. However, these methods are expensive and they cannot be applied in all cases. Adhesive bonding is a general bonding technology that enables to bond heterogeneous materials in effective way (Müller et al. 2013). The research results showed that it was suitable to use adhesives containing the filler (Müller et al. 2013). Their advantage is that they serve as a binder and they show increased wear resistance at the same time (Müller et al. 2013).

A possible application area of polymeric particle composite is the renovation of parts of soil processing machines (Valášek et al. 2015). Following up the experiment, prototypes of plough blades, landside and exchangeable parts of a mould board were developed (Valášek et al. 2015). Their functional steel surface was adjusted by these composite systems and nowadays, practical field tests are taking place (Valášek et al. 2015). An advantage of polymeric composite materials based on the particle filler is their decreased adhesion when processing the damp soil and related arising friction influencing the consumption of fuels (Valášek et al. 2015).

Renovation of agricultural machines such as tractors or harvesters, namely cementation of damaged surfaces, broken lines of operating liquids, sealing of leaks etc., is another application possibility of polymeric particle composites. These methods are used namely at the agricultural machines where acquisition of new parts is impossible, e.g. at old machines to which spare parts are not already possible to gain.

Particle fillers, especially short carbon fibres, improved the mechanical properties of the nanoclay filled PA66/PP composite. Graphite and Al_2O_3 are some of the fillers that are effective in reducing friction and wear (Suresha, Ravi Kumar 2010). Inorganic particles are well known to enhance the mechanical and tribological properties of polymers and polymer-based composite materials. It was found that the friction and wear properties varied continuously with the compositions for most polymer blends and the particle size plays an important role (Palabilyik, Bahadur 2000, 2002).

The filler of composite material is different: Al_2O_3, SiC, glass beads, minerals, various metals and rubber particles. Mechanical properties of polymeric composites strongly depend on the particle and its size (Shao-you Fu et al. 2008). The particle size and the volume have an obvious impact on these mechanical properties.

The aim of this study was to investigate mechanical wearing and hardness effects on polymeric materials. Various modifications of polymeric particle reactoplastic (a two-component adhesive), composites, Polyamide (PA6) and Polyethylene (PE) were tested. Reactoplastic was the comparing standard. The polymeric particle composites research and production were focused on dependence among a two-component epoxy adhesive and various concentrations and fractions of hardening particles of corundum, silicon carbide and glass.

MATERIAL AND METHODS

The object of the experiments was a particle polymeric composite, whose continuous phase was in the form of a two-component epoxy adhesive CHS Epoxy 1200 (hardener P11 – Diethylenediamine) and discontinuous phase (reinforcing particles) were particles of corundum Al_2O_3 (marked C), silicon carbide SiC (marked SC) and glass (marked G).

Following fillers were used (indication: fraction size (specific particle size in micrometres)):

- corundum – C60 (260 μm), C80 (185 μm), C100 (129 μm), C240 (44.5 μm), C400 (17.3 μm), C800 (6.5 μm) and C1000 (4.5 μm).
- Silicon carbide – SC60 (260 μm), SC80 (185 μm), SC100 (129 μm) and SC220 (58 μm),
- Glass ballotini – G10 (250 μm), G112 (200 μm), G134 (150 μm) and G159 (90 μm).

In Tables 1 and 2, variants of composite systems tested in the experiment are stated. The mean of the test specimens was 15.5 ± 0.1 mm and their height

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Table 1. Variants of experiment – One-component composite material

Variant of experiment	Filler concentration (vol. %)	Specific size of particles (μm)
C60	30	260
C80	30	185
C100	30	129
C240	30	44.5
C400	30	17.3
C800	30	6.5
C100	30	4.5
G10	30	250
G112	30	200
G134	30	150
G159	30	90
SC60	30	260
SC80	30	185
SC100	30	129
SC220	30	58

was 20 ± 0.1 mm. The shape and sizes of the PA6 and the PE test specimens were prepared by means of the machine chipping size. The shape and sizes of the epoxy and the polymeric particle composite test specimens were prepared by means of the casting in the forms from Lukapren. The matrix in the composite system was the resin on the basis of the two-component epoxy adhesive CHS-EPOXY 1200 (marked Epoxy 1200). The curing of the composite systems and the resin lasted 7 days at the temperature 22 ± 2°C.

The polymeric particle composites were cast into forms prepared in advance under the laboratory conditions and they were prepared with an amount of the filler in the matrix expressed by volume percentage.

The concentration of all fillers content in the composite material was set as 30 % and this concentration followed from the following pieces of knowledge:

– Own measurements for a purpose to find the maximum concentration of fillers with respect to mechanical properties with an emphasis on the abrasive wear resistance and hardness,
– Preparation of the composite materials itself consisting in mechanical mixing of all components when it was not practically feasible to reach higher concentration than 30% at given materials and given particle sizes at this manual way of the production.

Suggested composite materials are divided gradually according to the content and amount of components from which they consisted of. At first, the composite material consisting of the matrix and one component was suggested and further the hybrid composite materials which contain either two same components or two different components and finally the composite material consisting of three different components. The hybrid composite material combining two fillers was prepared with various ratios of these components but together it always contained 30%.

The concentration of the filler in the matrix is indicated by the volume fraction of filler v_p. Another

Table. 2. Variants of experiment – Hybrid composite material combining three different components

Variant of experiment	Filler concntration (vol. %)			Specific size of particles (μm)		
	G	*C*	SC	G	C	SC
C60:SC60:G10 1:1:1	10	10	10	250	260	260
C60:SC60:G10 4:1:1	5	25	5	250	260	260
C80:SC80:G112 1:1:1	10	10	10	200	185	185
C80:SC80:G112 4:1:1	5	25	5	200	185	185
C100:SC100:G134 1:1:1	10	10	10	150	129	129
C100:SC100:G134 4:1:1	5	25	5	150	129	129
C240:SC220:G159 1:1:1	10	10	10	90	44.5	58
C240:SC220:G159 4:1:1	5	25	5	90	44.5	58
C400:SC60:G10 4:1:1	5	25	5	250	17.3	260
C400:SC60:G10 1:4:1	5	5	25	250	17.3	260
C1000:SC60:G10 1:1:1	10	10	10	250	4.5	260
C1000:SC60:G10 4:1:1	5	25	5	250	4.5	260

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possibility of indication is the expression of the mass fraction of v_m. The mass fraction is not optimum due to the different densities of the matrix and filler. This difference is often very significant. The concentration of the filler in the matrix is considered as one of the most important parameters affecting the final properties of composite systems. The volume fraction of the filler is calculated according to the equation (1).

Epoxy density was 1.15 g/cm^3, corundum 4.0 g/cm^3, silicon carbide 3.2 g/cm^3 and glass 2.4 g/cm^3.

$$v_p = \frac{V_p}{V_c} \tag{1}$$

where: v_p – volume fraction of filler (–); V_p – volume of filler (cm^3); V_c – volume of composite (cm^3)

A necessary amount of the matrix was weighed at the preparation of the composite systems. The matrix mass (m_m) was weighed on digital scales with sensitivity 0.01 mg and the mass of the filler of one added component (m_p) was calculated to this mass according to the equation (2), which was used for calculation of the composite material consisting of three components, in order to keep required volume percentages of the filler (the filler ratio) in the matrix (v_p).

$$m_p = \frac{\dfrac{m_m}{\rho_m}}{100-(v_{p1}+v_{p2}+v_{p3})} \times \rho_p \times v_{p1} \tag{2}$$

where: m_p – mass of filler (g); m_m – mass of matrix (g); ρ_p – density of filler (g/cm^3); ρ_m – density of matrix (g/cm^3); v_{pX} – ratio of particular fillers in matrix (%)

The abrasive wear resistance was tested on a rotating cylindrical drum device with the abrasive cloth of the grain size P60 (a specific size of bound abrasive particles of corundum 260 μm), P120 (125 μm) and P220 (68 μm) according to the standard CSN 62 1466. The testing machine with the abrasive cloth consists of the rotating drum on which the abrasive cloth is affixed by means of a bilateral adhesive tape (Fig. 1). The test specimen is hold in the pulling head and during the test, it is shifted by means of the mowing screw along the abrasive cloth from the left edge of the drum to the right one. The test specimen is in contact with the abrasive cloth and it covers the distance of 60 m. During one drum turn of 360° the test specimen left above the abrasive cloth surface. Consequent impact of the test specimen simulates the concussion. The pressure force is 10 N.

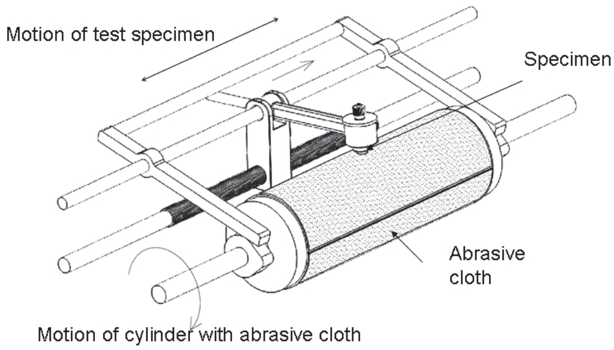

Fig. 1. Device for testing of abrasive wear resistance

The test principle corresponds to "two-body abrasion with impact" when firmly bonded hard particles penetrate the surface and harder particles wear out softer material during the mutual motion of the particles. This process leads to the material separation and consequently to the mass and volume material losses. The mass losses were weighed on digital analytic scales with sensitivity 0.01 mg.

The tested sets were mutually compared using F-test from the point of view of the influence on the adhesive bond tensile lap-shear strength. The zero hypothesis H_0 presents the state when there is no statistically significant difference ($p > 0.05$) among the tested sets of data from their mean values point of view.

The hardness is defined as the resistance of the material to penetration of foreign body or as the resistance of the material to plastic deformation. The hardness test according to Brinell follows the standard ČSN EN ISO 6506:2015. At this test, the penetrating body (a small ball of a mean D) pushes itself into the surface of the test sample and after reducing the load of the testing equipment the mean of the imprint, which stays preserved on the surface, is measured. The hardness experimentally measured by the method according to Brinell had the loading force 2.452 kN for the time 30 s, the mean of the indentor was 10 mm.

RESULTS

Volume losses for the epoxy resin Epoxy 1200 (the comparing standard) without filler for the cloth P220 was 0.3473 ± 0.0017 cm^3, for the cloth P120 0.5198 ± 0.0021 cm^3 and for the cloth P60 1.3572 ± 0.0038 cm^3. Experiment results are shown in Fig. 2.

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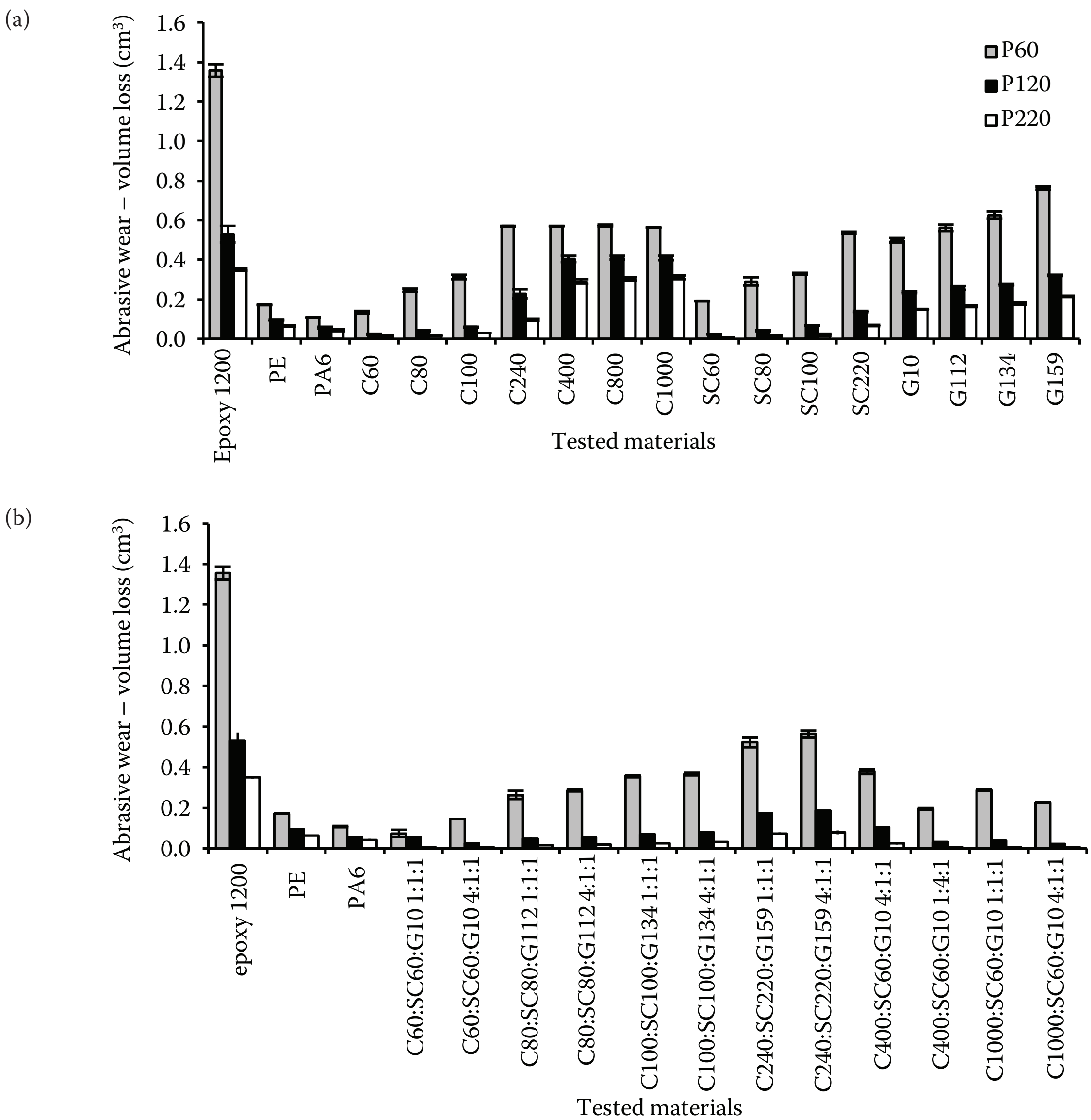

Fig. 2. Wear resistance of the tested materials – one-component composite material (a) and hybrid composite material combining three different components (b)

One-component composite material

Based on the results measured in the first chapter concerning one-component composite material where the filler is either Al_2O_3 or SiC or glass ballotini, it can be stated that adding particles of any type or size led to the improvement of the abrasive wear resistance, where higher particle size caused smaller volume losses. The best abrasive wear resistance was recorded at the composite system filled with particles of $Al_2O_{3;}$ the improvement was of 90% compared to the unfilled epoxy resin for the cloth P60 (the volume loss 0.1341 ± 0.0089 cm^3) and of 77.5% for the cloth P120. The best result for the cloth P120 was reached at SiC, where the increase was of 61%. When comparing the abrasive wear resistance of the industrially produced materials PE and PA6, they reached similar values as the composite materials filled with Al_2O_3 particles of the size 260 μm (C60).

The results of ANOVA (F-test) did not confirm the hypothesis H_0 for all three abrasive clothes P220, P120 and P60 (p = 0.0000) in terms of the influence of Al_2O_3 particles size in the composite material on the abrasive wear resistance; i.e. there is a difference among particular composite materials with various particle sizes from 260 μm for the fraction C60 to 4.5 μm for the fraction C1000 at the 0.05 significance level.

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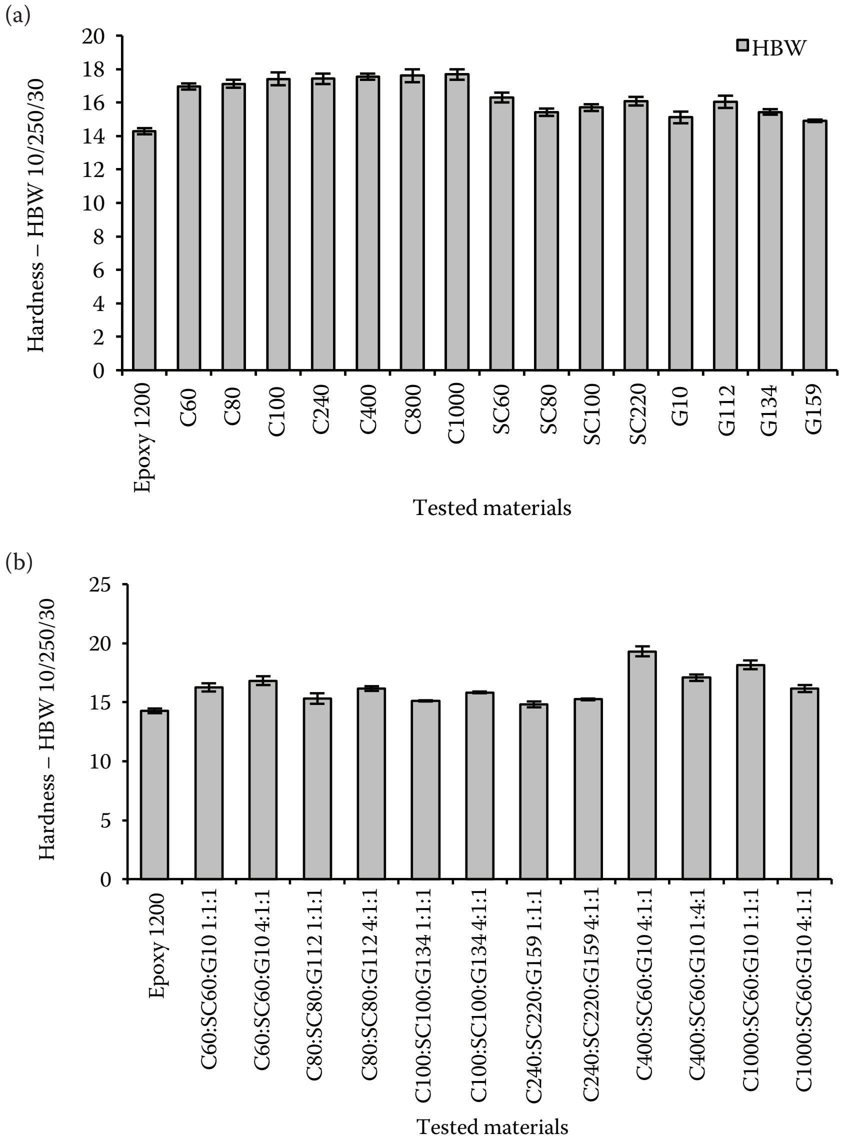

Fig. 3. Hardness of the tested materials – one-component composite material (a) and hybrid composite material combining three different components (b)

The results of ANOVA (*F*-test) did not confirm the hypothesis H_0 for all three abrasive clothes P220 (p = 0.0007), P120 (p = 0.0003) and P60 (p = 0.0002) in terms of the influence of the SiC particles size in the composite material on the abrasive wear resistance; i.e. there is the difference among particular composite materials filled with various sizes of SiC particles at the 0.05 significance level.

The results of ANOVA (*F*-test) did not confirm the hypothesis H_0 for all three abrasive clothes P220 (p = 0.0009), P120 (p = 0.0050) and P60 (p = 0.0016) in terms of the influence of the glass ballotini particles size in the composite material on the abrasive wear resistance, i.e. there is the difference among particular composite materials filled with various sizes of the glass ballotini balls at the 0.05 significance level.

The hardness results of one-component composite material are given in Fig. 3a. Values of the hardness of unfilled matrix in the case of the epoxy resin Epoxy 1200 amounted to 14.28 ± 0.19 HBW 10/250/30. At the composite materials filled with particles of Al_2O_3 the highest value of the hardness 17.54 ± 0.18 HBW 10/250/30 corresponded to the fraction C400 and 17.81 ± 0.38 HBW 10/250/30 to the fraction C400. At these composite systems, the hardness was increased of 23% compared to the pure matrix (epoxy 1,200). In terms of the influence of the particles Al_2O_3, SiC and glass ballotini in one-component composite material on the hardness, the hypothesis H_0 (p = 0.0000) was not confirmed from the results of ANOVA (*F*-test), i.e. there was the difference among particular composite materials with different size of the filler particles at the 0.05 significance level.

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Hybrid composite material combining three different components

The results of the abrasive wear resistance measurement show as the most resistant such material which contains the highest particle sizes and the representation of these particles in the composite material is even at the same time. The even representation of particular particles of Al_2O_3, SiC and glass ballotini has also a positive influence and it resulted in reaching the improvement of the abrasive wear resistance compared to composite materials in which the component of Al_2O_3 was represented in higher ratio. At the composite materials with fillers with the same particle sizes, the highest decrease of the volume losses of 94% was reached for the cloth of the grain size P60 at the composite material consisting of 10% of the glass ballotini of the fraction G10 (250 μm), 10% of Al_2O_3 of the fraction C60 (260 μm) and 10% of SiC of the fraction SC60 (260 μm) compared with the epoxy resin without filler.

From the second group of three-component composite materials where there were not only various materials but also various combinations of the particle sizes, the smallest volume losses were obtained at materials with higher ratio of Al_2O_3 particles. The best results of the abrasive wear resistance obtained for the cloth of the grain size P120 were of 96% and the improvement amounted to 98% for the cloth of the grain size P220 compared with the epoxy resin without the filler. The results of ANOVA (F-test) did not confirm the hypothesis H_0 for all three abrasive clothes P220 (p = 0.0001), P120 (p = 0.0000) and P60 (p = 0.0000) in terms of the influence of the ratio of three different components with similar sizes of the particles in the composite material on the abrasive wear resistance, i.e. there is a difference among particular tested hybrid composites with three different components at the 0.05 significance level.

The results of ANOVA (F-test) did not confirm the hypothesis H_0 for all three abrasive clothes P220 (p = 0.0426), P120 (p = 0.0003) and P60 (p = 0.0002) in terms of the influence of the ratio of three different components with various sizes of the particles in the composite material on the abrasive wear resistance, i.e. there is a difference among particular tested hybrid composites with three different components with various sizes of the particles at the 0.05 significance level.

Basavarajappa et al. (2010) dealt with the abrasive wear of the polymeric particle composite that reached a significant improvement of the wear resistance at filling the composite with SiC particles. This conclusion was certified with another filler, too.

Resultant properties of the hybrid composite material are influenced by many aspects including its components. By adding the filler into a relatively expensive matrix in the form of the epoxy resin the

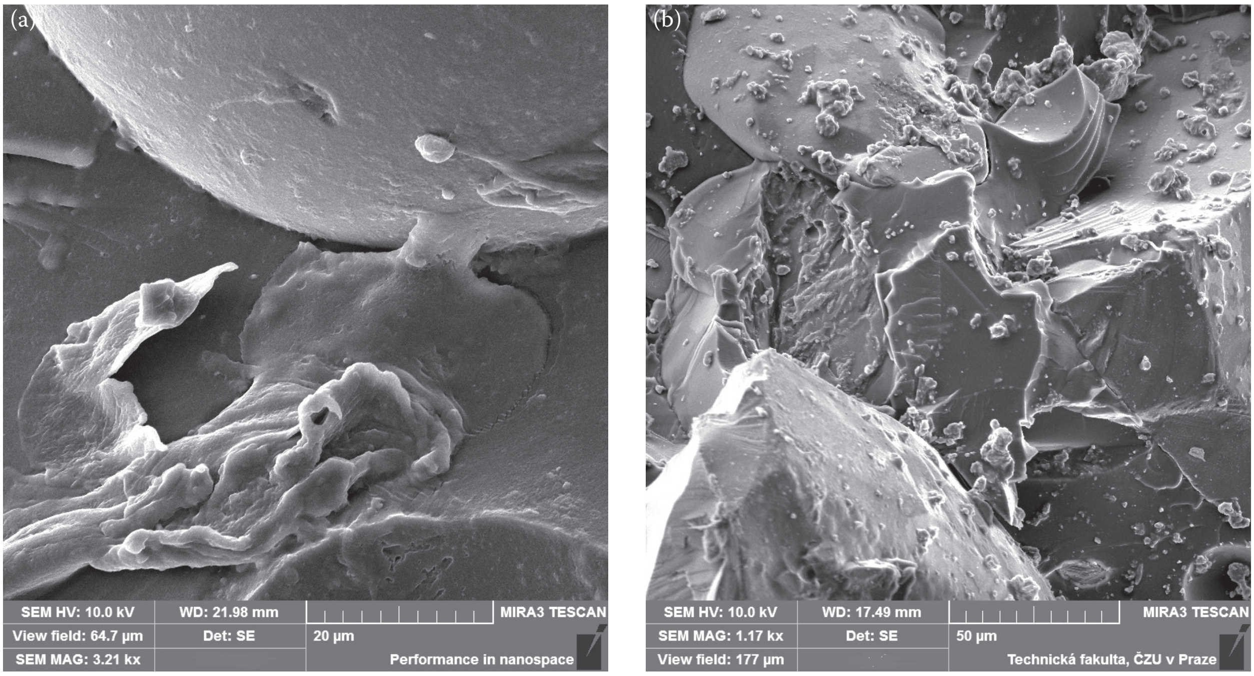

Fig. 4. Fracture surface of sample with G159 (a) and of sample C1000:SC60:G10 4:1:1 (b) – both secondary electrons

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price is decreased. The reason is relatively cheap fillers that substitute a part of the epoxy resin in the composite material. Also, an increase of the wear resistance occurs together with the lowering of the price of the resultant material at the application of suitable fillers. This state was experimentally confirmed.

The results of the hardness of the hybrid composite material combining three different components are shown in Fig. 3b. The highest increase of the hardness was measured at the composite system C400:SC60:G10 at the ratio 4:1:1. The hardness value was 19.31 ± 0.44. It was the increase of 35% compared to the hardness of the matrix. In terms of the influence of Al_2O_3, SiC and glass ballotini particles in the hybrid composite material combining three different components on the hardness, the hypothesis H_0 (p = 0.0000) was not confirmed from the results of ANOVA (F-test), i.e. there is a difference among particular composite materials with various sizes of the filler particles at the 0.05 significance level.

Owing to very complicated process of bonds within the hybrid composite, the scanning electron microscopy was used in the fracture surface. It is possible to indicate a correct bond between the adhesive and the filler (Glass ballotini, Fig. 4a) from the picture of the fracture surface of filled two-component adhesive.

There is a visible distribution of large and small particles of corundum, silicon carbide and glass ballotini fillers in Fig. 4b.

Chang et al. (2001) proved in their experiments that the irregular shape of the particles ensures good interaction between the matrix and the filler. Farraf Noor Ahmad et al. (2008) ascertained that the irregular shape of particles showed worse mechanical properties probably owing to the separation between the matrix and the filler. Good interaction between the filler and the matrix is given in Fig. 4. It is obvious from the result that it did not depend on the shape of the filler.

CONCLUSION

Following conclusions can be set from the results of the experiments focused on determining the wear resistance of polymeric particle composites:

– The significant improvement of the measured values at measuring the abrasive wear resistance was reached at the hybrid composite materials filled with three different components where the improvement amounted to 98% compared to the epoxy resin without the filler.
– The particle size influenced the properties of the polymeric composite when the particles of higher size brought the positive influence on the wear resistance and on the hardness HBW 10/250/30.
– The influence of the filler on the wear resistance was statistically proved by means of the ANOVA F-test at the 0.05 significance level. The influence of the filler on the hardness HBW 10/250/30 was statistically proved by means of the ANOVA F-test at the 0.05 significance level.
– The scanning electron microscopy proved good interfacial bonds among particles of the filler with both irregular as well as regular shape.

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