Tribological properties of AC44200 based composites strengthened with Al₂O₃ particles

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Abstract

The paper presents a research on abrasion resistance of aluminium-based composites consisting of EN AC-44200 matrix reinforced with Al₂O₃ particles. The examinations revealed that wear intensity of the composites decreased with increasing volume fraction of the particles. Much more intensive abrasive wear was observed on the first kilometre in comparison to the wear on the subsequent distances, i.e. from 1 to 3.5 km and from 3.5 to 8.5 km of the wear distance. Microscopic examinations permitted determining the way and type of wear occurring in the examined materials. In the case of the AC-44200 matrix, typical adhesive wear is observed. In composite materials however, abrasive wear prevails over adhesive wear. Increased volume fraction of Al₂O₃ particles in composite materials results in increasing friction factor in average by 0.250 per each 10 vol.%. Wear of the cast-iron counterspecimen is also strongly dependent on volume fraction of the reinforcing particles. The counterspecimen demonstrates the largest wear when working in contact with a composite material containing 40 vol.% of Al₂O₃ particles.

Key words: composite materials, tribological properties, aluminium oxide particles

1. Introduction

Aluminium-based composite materials reinforced with ceramic particles belong to the material group with very good tribological properties. With this respect, they are applied for the components subject to intensified abrasive wear under significant loads. Nowadays, attempts are made to apply these materials in the existing mechanisms and devices that components are often made of traditional materials, e.g. cast iron. One of the most frequently mentioned possible applications are parts of braking systems. Therefore, it seems expedient to determine behaviour of these materials versus cast iron used industrially for brake disks. In this specific application, these materials must stand extremely hard service conditions consisting in intensive abrasion under high surface pressures at variable temperatures. As the research [1,3] indicates, resistance of composite materials to abrasive wear, as well as their rigidity and hardness, increase with increasing volume fraction of the reinforcing phase. However, depending on chemical composition of the materials making a friction pair and on their working conditions, the wear mechanisms can be significantly different in individual cases. The factors influencing the wear process include also in particular: chemical composition of the matrix material, volume fraction of the reinforcing phase, its kind, size and arrangement [2, 4-15]. A significant role is also ascribed to the shape of the reinforcing
particles [3]. Important is also the preliminary stage of running-in process [1] that can significantly affect intensity of the material wear. During the abrasion process, the materials are subject to deformations that course depends on temperature and load. Under this influence, structure of the material changes and, in consequence, some of its properties change as well. All these factors influence abrasion resistance of the materials and their service life.

**Materials and methodology of the research**

The research was aimed at determining the influence of volume fraction of the reinforcing particles on abrasive wear of composite materials consisting of EN AC-44200 matrix and Al₂O₃ reinforcing particles. The materials to be examined were prepared by pressure infiltration of porous preforms made of ceramic Al₂O₃ particles. Chemical composition of the matrix alloy EN AC-44200 is given in Table 1. The infiltration process was carried-out at 100 MPa. The examinations were performed for the composite materials containing 10, 20, 30 and 40 vol.% of reinforcing particles.

Table 1. Chemical composition of EN AC-44200

<table>
<thead>
<tr>
<th>Weight fraction [%]</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Zn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5 ÷ 13.5</td>
<td>0.55</td>
<td>0.05</td>
<td>0.35</td>
<td>0.10</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Al – remainder</td>
<td></td>
<td></td>
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</table>

Ceramic preforms were made of Al₂O₃ particles with size from 3 to 6 μm and density ρ = 3.95 g/cm³. Because of porous structure of the preforms, the produced composite materials consisted of the areas filled with matrix, arranged alternately with those of high concentration of the reinforcing particles. Quantity of these areas, their size and arrangement depended on volume fraction of the reinforcing particles. Figure 1 shows an exemplary microstructure of the composite containing 10 vol.% of Al₂O₃ particles.

Examination of abrasion resistance was performed by the "pin-on-disk" method, in dry friction conditions. Specimens for testing were prepared in form of cylinders dia. 7.1 mm. The abrasion process took place on the specimen face, pressed against face surface of the rotating counterspecimen under unit pressure of 1 MPa. The counterspecimen disk dia. 90 mm, made of cast iron with hardness of 180 HB, rotated at 318 rpm. Before testing, all specimens were preliminarily run-in on a distance of 0.35 km to obtain good contact with the counterspecimen on the entire surface. For comparative reasons, the examinations were also performed on the specimens made of non-reinforced matrix material manufactured with the pressure of 100 MPa (infiltration pressure of the porous preforms).

**Results and discussion**

The test results indicate that abrasive wear of the composite materials decreases with increasing volume fraction of ceramic particles, see Fig. 2.
However, this process runs with different intensity on the abrasion distance from 0 to 1 km than on the subsequent distances from 1 to 3.5 km and from 3.5 to 8.5 km. With this respect, the relationship between wear intensity and volume fraction of $\text{Al}_2\text{O}_3$ particles was divided to 2 stages:

- stage I from 0 to 1 km of abrasion distance;
- stage II from 1 to 3.5 km and from 3.5 to 8.5 km of abrasion distance (measurement results obtained on the distance from 1 to 3.5 km are equal to those obtained on the distance from 3.5 to 8.5 km).

Intensity of wear on the 1\textsuperscript{st} kilometre of the abrasion distance (stage I) is significantly higher than that on the distances from 1 to 3.5 km and from 3.5 to 8.5 km (stage II), especially for the materials containing 10 vol.% of the particles. As the volume fraction of the particles in the composite materials rises, differences in abrasion intensities on individual stages become smaller.

Since the results on individual abrasion distances included in the stage II were equivalent, the relationship between volume fraction of $\text{Al}_2\text{O}_3$ particles and intensity of abrasive wear was described by one power function:

$$y = 4.35x^{-0.29}$$  \hspace{1cm} (1)

The adjustment coefficient for the obtained results is $R^2 = 0.98$.

From among the examined materials, the non-reinforced alloy AC-44200 undergoes the most intensive wear, see Fig. 3. In this case as well, intensity of abrasive wear on the 1\textsuperscript{st} kilometre of the distance is slightly higher than that on the distances from 1 to 3.5 km and from 3.5 to 8.5 km.

Microscopic observations were performed on the surfaces obtained by cutting the specimens in the plane perpendicular to the abrasion plane. Figure 4 shows the microstructure at the plane perpendicular to the abrasion surface of a non-reinforced AC-44200 specimen.

Small ability of the alloy AC-44200 for plastic deformation results in creating a characteristic buildup in the edge specimen zones. On its surface, adhesively adhering slices of the abraded material are often observed. During abrasion, its fragments are cyclically built-up and spalled-off. It should be noted that the specimens were weighed together with the strongly adhered buildup.

Fig. 4. Friction surface of the alloy AC-44200

![Friction surface of the alloy AC-44200](image)

The specimens with 10 vol.% of $\text{Al}_2\text{O}_3$ particles also show the tendency to build-up. However, the buildup in these materials is much smaller, see Fig. 5. They are much more brittle than the matrix alloy that results in their systematic spalling. This phenomenon was not observed in the specimens with higher fraction of the particles, i.e. 20, 30 and 40 vol.%.

Fig. 5. Friction surface of the alloy AC-44200 with 10 vol.% of $\text{Al}_2\text{O}_3$ particles

![Friction surface of the alloy AC-44200 with 10 vol.% of $\text{Al}_2\text{O}_3$ particles](image)
composites containing 10 vol.% of Al₂O₃ particles, changes of the material structure are visible till ca. 60 μm from the abrasion surface. Increasing fraction of the particles by each 10 vol.% reduces the deformation range by ca. 15 μm.

Microscopic analysis of the non-reinforced alloy AC-44200 indicates typically adhesive nature of wear. Observations revealed extensive areas smeared by flakes of the material torn-off from the abraded surface. During the test, these flakes were squashed and rubbed into the specimen surface that consequently resulted in characteristic “scaly” surface, see Fig. 8.

Fig. 6. Friction surface of the alloy EN AC-44200

On the abrasion surfaces of the specimens are observed also embedded or adhering products of abrasive wear. They are from the materials of both the specimens and the cast-iron counterspecimen, see Fig. 7.

Fig. 7. Friction surface of the composite material AC-44200 with 20 vol.% of Al₂O₃ particles

Size of spalled fragments of the cast-iron disk reaches even 120 μm, intensifying the wear processes. In the specimens containing 30 and 40 vol.% of the particles, the wear products are seldom embedded into the material. They are usually deposited on the abrasion surface with visible interface between them. In the abrasion process, they wear the composite surface, shoving ahead agglomerations of the matrix material containing ceramic particles, see Fig. 7.

No cracks were observed on the surfaces of non-reinforced specimens, but only sporadically occurring shallow scratches parallel to the abrasion direction. The non-reinforced specimens very seldom show fragments of the counterspecimen material on their surfaces.

Surface observations of the composite materials explicitly indicate reduction of the adhesive wear type, dominating in the non-reinforced specimens of AC-44200. In the materials containing 10 vol.% of Al₂O₃ particles, quantity and size of the adherively adhering flakes of the abraded material were reduced ca. 90%. However, number of grooves was increased and they became significantly deeper and wider. The largest scratches, up to 150 μm wide and up to 60 μm deep, occurred mainly in the specimens containing 30 and 40 vol.% of Al₂O₃ particles.

In these materials, numerous deep craters are also present. They are created as a result of tearing-out from the surface extensive pieces of the material containing ceramic particles. In the other craters, most often accumulated are the abrasion products like loose Al₂O₃ particles, agglomerations of the matrix with particles and crushed fragments of the counterspecimen, see Fig. 9.

Moreover, in the composite materials containing from 20 to 40 vol.% of Al₂O₃ particles forming transverse cracks, perpendicular to the abrasion direction was observed. During the test, material bands separated by these cracks were systematically torn from the specimen surface, see Fig. 10.

Number of these cracks and their length significantly increased with increasing fraction of the reinforcing phase. In addition, in the materials with the highest fraction of the particles (40 vol.%), narrow material bands (3 to 7 μm thick) between the transverse cracks were subject to fragmentation.
Figure 11 shows the relationship between friction coefficient and volume fraction of the reinforcing $\text{Al}_2\text{O}_3$ particles in AC-44200 matrix. The relationship between friction coefficient and volume fraction of the reinforcing $\text{Al}_2\text{O}_3$ particles is of linear nature for all the examined composite materials. The friction coefficient increases with increasing fraction of the particles, in average by 0.250 per each 10 vol.% of $\text{Al}_2\text{O}_3$ particles. The relationship is similar on each considered abrasion distance. The highest values of the friction coefficient were obtained on the distance of 1 km, as a result of running-in the specimens. The smallest value of the coefficient was obtained for the non-reinforced AC-44200 alloy.

Figure 12 shows a roughness profile diagram of the counterspecimen surface after abrasion test on the distance 8.5 km. The obtained surface profiles indicate that reinforcing particles in composite materials strongly affect wear intensity of the counterspecimen. It can be assumed that each additional 10 vol.% of the $\text{Al}_2\text{O}_3$ particles gives in average a 30-µm deeper wear of the cast-iron disk. The smallest wear was found on the counterspecimen wearing with the non-reinforced AC-44200 alloy. In this case, the groove was in average ca. 30 µm deep. The largest wear was revealed by the counterspecimen contacting with the composite material containing 40 vol.% of $\text{Al}_2\text{O}_3$ particles.

The examinations showed also a slight influence of volume fraction of particles on average surface roughness $Ra$ of a crater bottom on the counterspecimen. The value $Ra$ grows with increasing volume fraction of the reinforcing particles from 7.4 µm at 10 vol.% to 9.1 µm at 40 vol.% of the particles. The roughness value of the counterspecimen disk before testing was 3 µm and resulted from the applied machining method.
Summary

1. Wear of the examined composite materials decreases with increasing volume fraction of ceramic reinforcing particles.
2. Wear process runs much more intensively and with higher friction coefficient \( f \) on the first kilometre of the friction distance than on the other applied friction distances 1 to 3.5 km and 3.5 to 8.5 km. Higher intensity of wear at the initial stage is related to creating in the specimen a structurally different zone (deformation of \( \alpha \) phase and disintegration of eutectic silicon particles) at some distance from the friction surface. This process takes place on the distance from 0 to 1 km.
3. During wear process of the non reinforced matrix material, dominating is adhesive wear. In turn, abrasive wear is dominating in the composite materials.
4. With increasing volume fraction of \( \text{Al}_2\text{O}_3 \) particles, the friction coefficient increases ca. 0.250 per each additional 10 vol.% of the reinforcing particles.
5. Higher volume fraction of \( \text{Al}_2\text{O}_3 \) particles in the composite materials results in more intensive groves forming of the counterspecimen material. Depth of groves of the cast-iron disk is ca. 30 \( \mu \)m larger per each additional 10 vol.% of the reinforcing particles.
6. Roughness Ra at the bottom of a crater on the counterspecimen increases with larger volume fraction of reinforcing particles in the composite materials from 7.4 \( \mu \)m at 10 vol.% to 9.1 \( \mu \)m at 40 vol.% of the particles.

Acknowledgment

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