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# Bending Strength of EN AC-44200 – Al<sub>2</sub>O<sub>3</sub> Composites at Elevated Temperatures

A. Kurzawa \*, J.W. Kaczmar

Politechnika Wrocławska, Faculty of Mechanical Engineering,  
 Department of Foundry Engineering, Plastics and Automation,  
 Smoluchowskiego 25, 50-372 Wrocław, Poland

\*Corresponding author. E-mail address: adam.kurzawa@pwr.edu.pl

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## Abstract

The paper presents results of bend tests at elevated temperatures of aluminium alloy EN AC-44200 (AlSi12) based composite materials reinforced with aluminium oxide particles. The examined materials were manufactured by squeeze casting. Preforms made of Al<sub>2</sub>O<sub>3</sub> particles, with volumetric fraction 10, 20, 30 and 40 vol.% of particles joined with sodium silicate bridges were used as reinforcement. The preforms were characterised by open porosity ensuring proper infiltration with the EN AC-44200 (AlSi12) liquid alloy. The largest bending strength was found for the materials containing 40 vol.% of reinforcing ceramic particles, tested at ambient temperature. At increased test temperature, bending strength R<sub>b</sub> of composites decreased in average by 30 to 50 MPa per 100°C of temperature increase. Temperature increase did not significantly affect cracking of the materials. Cracks propagated mainly along the interfaces particle/matrix, with no effect of the particles falling-out from fracture surfaces. Direction of cracking can be affected by a small number of agglomerations of particles or of non-reacted binder. In the composites, the particles strongly restrict plastic deformation of the alloy, which leads to creation of brittle fractures. At elevated temperatures, however mainly at 200 and 300°C, larger numbers of broken, fragmented particles was observed in the vicinity of cracks. Fragmentation of particles occurred mainly at tensioned side of the bended specimens, in the materials with smaller fraction of Al<sub>2</sub>O<sub>3</sub> reinforcement, i.e. 10 and 20 vol.%.

**Keywords:** Bending strength, Aluminium alloy composite materials, Aluminium oxide particles

## 1. Introduction

Devices and installations often operate at elevated temperatures. Thus, when producing new materials for design and applications in the new devices, considered is their behaviour not only at ambient temperature, but also at elevated temperatures. Increase of operating temperatures usually leads to reduction of mechanical and working parameters [1]. It is therefore important to know the phenomena and mechanisms accompanying wear and destruction of composite materials at elevated temperatures, as well as to determine temperature ranges of their safe operation.

Bending stresses are the basic ones accompanying loads of machine components and can cause their destruction [2]. This is why this research is aimed at evaluating bending strength of aluminium alloy EN AC-44200 (AlSi12) based composite materials reinforced with aluminium oxide particles at temperatures between 20°C and 300°C. Matrix of a composite material contains ceramic particles, so its plastic formability is limited in comparison to the non-reinforced matrix. However, deformability of the matrix increases with increasing temperature, according to the increased plasticity of the aluminium alloy matrix. In such conditions, depending on the applied stress, the particles can be displaced in plastic matrix or can be fragmented. The frequently found phenomenon is also their detaching from the

matrix under the applied stresses. One of the basic conditions of good mechanical properties at ambient and elevated temperatures is strong adhesive and mechanical bonding at the interfaces matrix/strengthening particles. Apart from quality of the interface, strength is affected by many technological parameters like infiltration pressure and temperatures of liquid base alloy [3], size of reinforcing particles [4-6] and temperature of preform, mould and pressing punch. A condition for achievement of high mechanical properties is also small rest porosity of castings [7] and properly carried-out heat treatment of composite material [8,9]. The materials described in this work, manufactured as pressure castings (squeeze casting), are characterized by the homogeneous distribution of ceramic particles conditioned by preform structure and good adhesive and mechanical bonding at the interfaces between reinforcing ceramic  $\text{Al}_2\text{O}_3$  particles and EN AC-44200 (AlSi12) matrix [10,11].

## 2. Experimental methods

Composite materials were manufactured by squeeze casting of porous preforms with the liquid EN AC-44200 (AlSi12) matrix aluminium alloy [10-14,17]. As reinforcement of the composites, preforms made of  $\text{Al}_2\text{O}_3$  particles were applied. The ceramic particles contained 99.7% of  $\text{Al}_2\text{O}_3$  and admixtures of  $\text{Na}_2\text{O}$ ,  $\text{SiO}_2$  and  $\text{Fe}_2\text{O}_3$ . Density of  $\text{Al}_2\text{O}_3$  particles used in the research was  $3.95 \text{ g/cm}^3$  and their particles size ranged between 3 and  $6 \mu\text{m}$ . The preforms were made with the application of water-glass as the binder, hardened with flowing  $\text{CO}_2$ . After moulding and hardening, they were subjected to firing at  $960^\circ\text{C}$ , which guaranteed obtaining of strong joints between ceramic particles and, in consequence, proper strength of the preforms during infiltration with liquid EN AC-44200 (AlSi12) alloy. A special feature of the preforms facilitating their infiltration was open porosity obtained by proper manufacturing procedure [10,11,14,15]. For the composites manufacturing preforms containing 10, 20, 30 and 40 vol.% of  $\text{Al}_2\text{O}_3$  particles (preforms characterised by the open porosities of 90, 80, 70 and 60%) were prepared. An exemplary structure of manufactured ceramic preform from alumina particles is shown in Fig. 1, where typical joints (bridges) of water-glass between adjacent ceramic particles are visible.

Matrix of the examined composite materials was the casting alloy EN AC-44200 (AlSi12) characterised by good castability and medium mechanical properties. In mechanical engineering, this alloy is applied for the loaded parts of machines and devices working in difficult conditions [16]. Fig. 2 shows structure of the unreinforced EN AC-44200 (AlSi12) alloy and its chemical composition is given in Table 1.

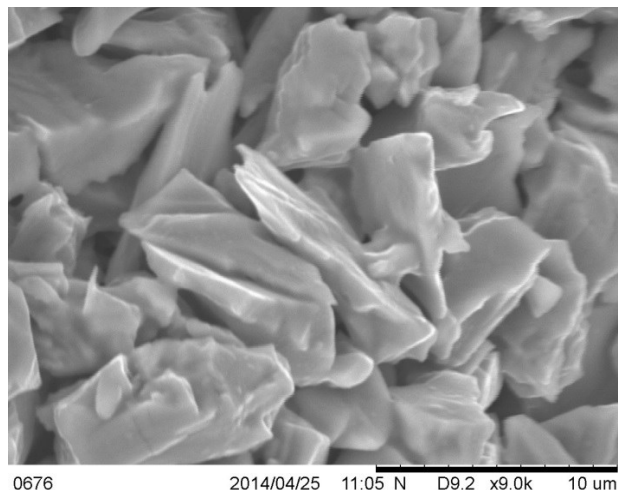


Fig. 1. Microstructure of a ceramic preform fracture, characterised by the open porosity. Visible linking bridges from water-glass between ceramic  $\text{Al}_2\text{O}_3$  particles

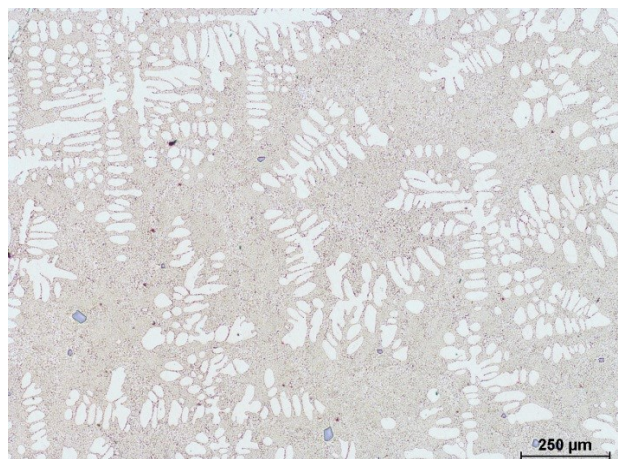


Fig. 2. Microstructure of cast EN AC-44200 (AlSi12) aluminium alloy

Table 1.  
Composition of EN AC-44200 (AlSi12) matrix alloy

Weight fraction [%]	Si	Fe	Cu	Mn	Zn	Ti
EN AC-44200	10.5-13.0	0.55	0.05	0.35	0.10	0.15
Al – remainder						

Infiltration of the porous preforms was carried-out applying a special mould and punch mounted at the hydraulic press PHM-63. The preforms mounted in a steel mould and heated to  $500^\circ\text{C}$  were infiltrated with liquid EN AC-44200 (AlSi12) alloy at  $720^\circ\text{C}$ , and then pressure of 100 MPa was exerted by the pressing punch. Pressure was maintained until the complete solidification took place. An exemplary structure of this way produced composite material reinforced with 20 vol.% of  $\text{Al}_2\text{O}_3$  particles is shown in Fig. 3.

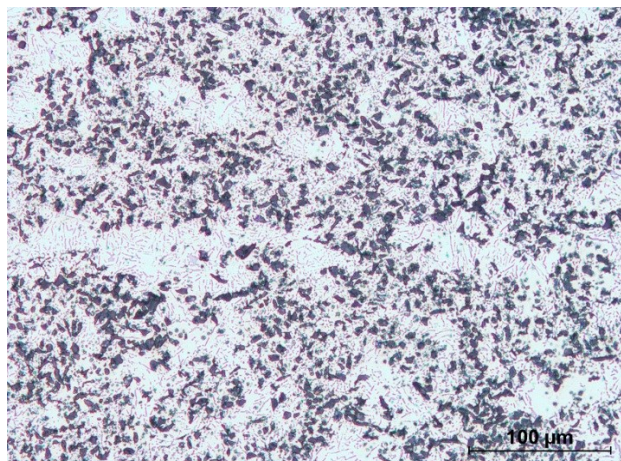


Fig. 3. Microstructure of composite material EN AC-44200-20 vol.% of  $\text{Al}_2\text{O}_3$  particles

Specimens in the form of the rectangular prism ( $60 \times 10 \times 4$  mm) were cut-out from the castings. These specimens were next subjected to three-point bending tests at temperatures of 20, 100, 200 and 300°C. For comparative reasons, specimens made of non-reinforced EN AC-44200 (AlSi12) aluminium alloy were also examined in the same way. Bend tests were carried-out on a Tinius Olsen H25KT testing machine.

### 3. Results and discussion

#### 3.1. Microstructure

During microscopic observations of composite materials, special attention was paid to the role of the ceramic particles in crack propagation during bending. SEM examinations of fracture surfaces and microstructures close to the fracture surfaces were carried out. Microscopic observations of the unreinforced EN AC-44200 (AlSi12) castings confirmed that cracks propagate mostly along grain boundaries between phase  $\alpha$  and crystals of silicon, what was observed by us [18] in materials deformed by bending at ambient temperatures. Eutectic mixture can be relatively easily separated from secondary arms of dendrites, see Fig. 4. It was demonstrated by scanning microscopy examinations that after deformation by bending, sparse elongated, jagged structures of broken dendrites were detected, see Fig. 5 [18].

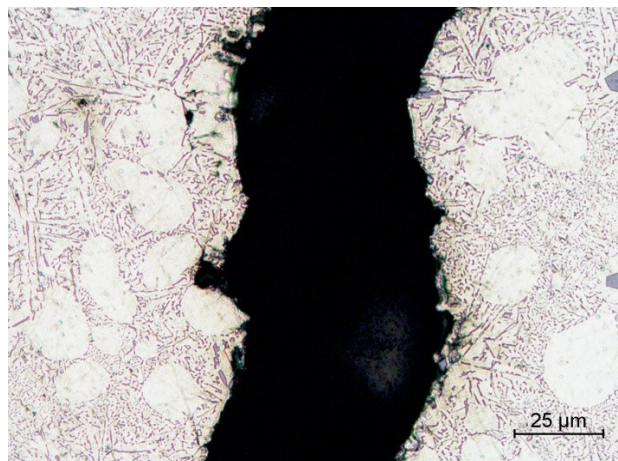


Fig. 4. Fracture in unreinforced EN AC-44200 alloy after bending at 20 °C

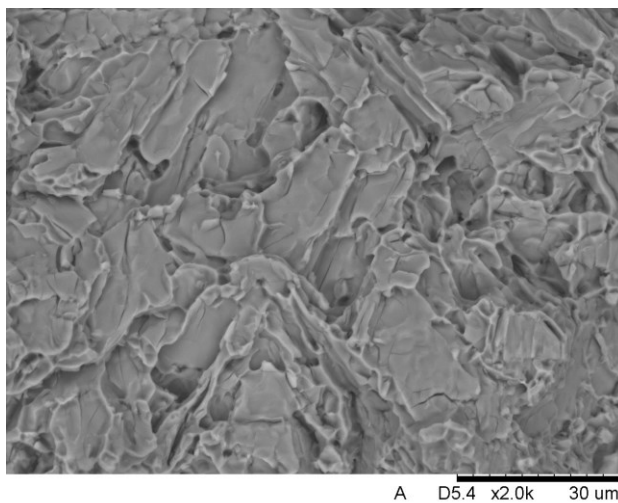


Fig. 5. Fracture surface of a specimen of EN AC-44200 after bending at 20 °C. Centre of fracture area [18]

Fracture surfaces of the composite materials based EN AC-44200 (AlSi12) matrix subjected to bending at 20 °C show brittle or mixed nature. Cracks propagate mainly along interphase boundaries particles - matrix. Unlike the other examined materials, those with 10 vol.% of reinforcement show a specific structure where the unreinforced areas of 50 to 80  $\mu\text{m}$  can be distinguished, located between bands of the matrix reinforced with the  $\text{Al}_2\text{O}_3$  ceramic particles. In these materials, cracks occur most often along interfaces between these areas, see Figs. 6a and 6b.

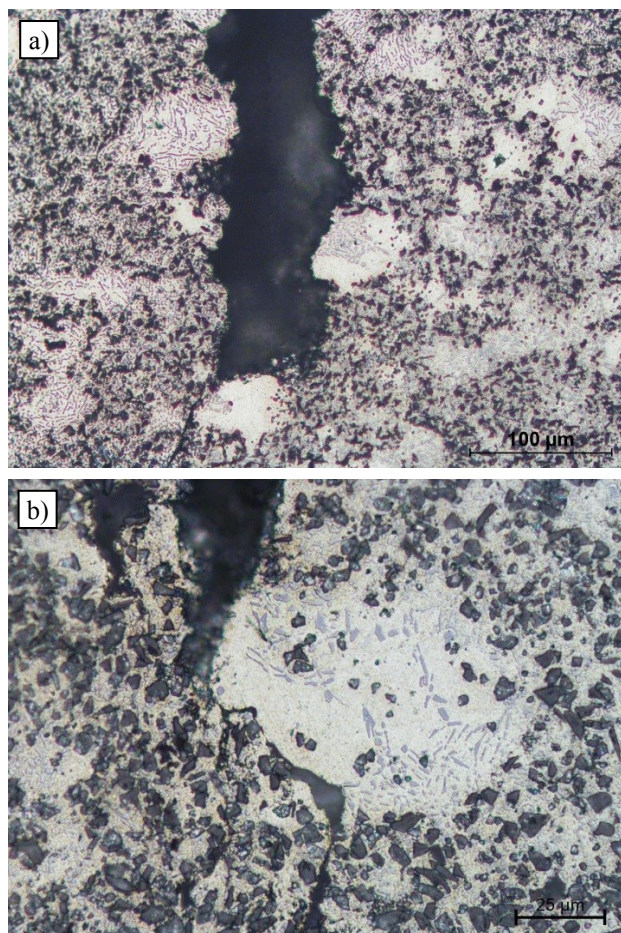
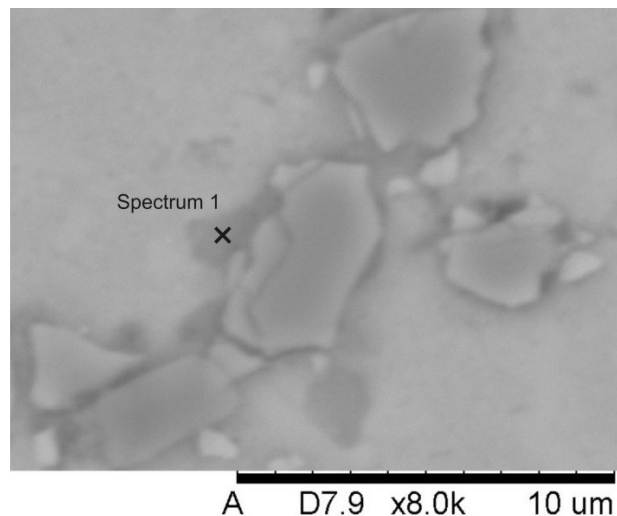


Fig. 6. Fractures after bending at 20°C, a) EN AC-44200 – 10 vol.% of  $\text{Al}_2\text{O}_3$  particles; b) EN AC-44200 – 10 vol.% of  $\text{Al}_2\text{O}_3$  particles with non-reinforced areas close to the crack

Moreover, in the material away from the main crack surface, slight deformation of the matrix material is observed, what can cause the breaking the anchored particles. A similar mechanism occurs also in the specimens containing 20 vol.% of reinforcing particles. In the materials containing 30 and 40 vol.% of  $\text{Al}_2\text{O}_3$  particles, no fragmentation of the particles in the vicinity of the fracture surface is observed after bending at 20 °C. In these materials, the privileged places of cracks are mostly boundaries of the ceramic particles, but numerous cracks of the particles are also observed, which proves their direct participation in stress transmission. Generally, in all the examined composites, the particles located at the fracture surfaces show strong adhesive and mechanical bonds with the matrix material. An exception are sparse places with structural defects like agglomerations of tightly packed particles or concentrations of the unreacted binder with the matrix. In the case of such agglomerations of particles, infiltration sometimes is not complete and adjacent particles are not linked with the matrix material. By this way, local porosity appears influencing direction of cracking. The latter case results directly from manufacturing process of the preforms, based on application of inorganic binder. Hydrated sodium carbonate  $\text{Na}_2\text{CO}_3 \cdot n\text{H}_2\text{O}$  and silica creating during hardening of the binder

produce strong joints maintaining geometry of the preforms during their infiltration with liquid EN AC-44200 (AlSi12) aluminium alloy. However, with regard to high solidification rate of the castings, sparse places with not completely reacted silica are also present, see Fig. 7.



Spectrum 1

Element	Weight %	Atomic %
Si K	41.14	29,02
O K	53.76	66,58
Na K	5.10	4.40

Fig. 7. Phase analysis of composite material EN AC-44200–20 vol.% of  $\text{Al}_2\text{O}_3$  particles

According to the high brittleness of this phase and the relatively low strength, these areas can be also decisive for the direction of crack propagation.

In the areas containing structural defects, fractures are of more brittle nature, with partially torn-off particles. Presence of structural defects in the vicinity of the main crack results in delaminations and additional cracks propagating just through these areas. This type defects cause also rapid changes of a crack propagation direction.

Microstructure of fracture surroundings in the composite specimens tested at elevated temperatures is slightly different. In all the examined materials, especially closer to the areas of the bended specimens which are deformed by tension, number of broken particles increases with increasing temperature in direct vicinities of the main fracture. At the areas, where tensile stresses are prevailing, cracks of particles are observed at distances up to 60 µm from the fracture surface, see Fig. 8. In the material closer to the point of the plunger application, where compression stresses are dominant, a slightly smaller number of fragmented particles is observed. In the part of the specimen, which is compressed, places of separations of matrix from the strengthening particles at the interface occur more frequently. This phenomenon is intensified with the increasing test temperature from 20 to 300 °C. At larger distances from the fracture surface, deeper in the material, the particles remain unimpaired, with no marks of separation from the metallic matrix.

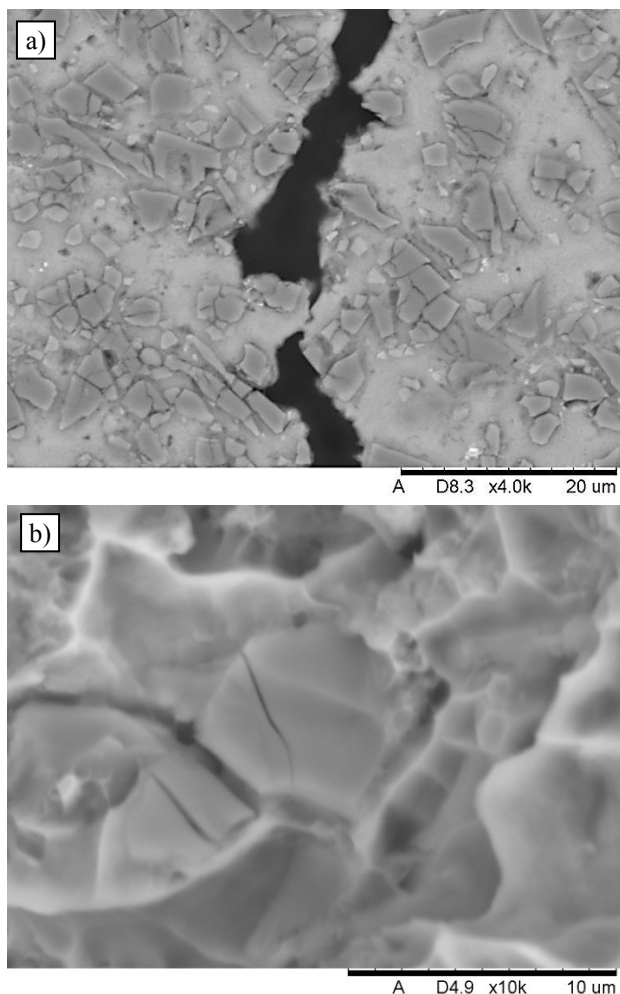


Fig. 8. Microstructure of composite material EN AC-44200 – 20 vol.% of  $\text{Al}_2\text{O}_3$  particles. Fracture after bending at 300 °C: a) fractures after bending b) surface after bending with visible cracked particles

### 3.2. Bending strength

Bending strength of an unreinforced specimen tested at 20°C is 345 MPa, ca. 10 to 30 % less than strength of composite materials. Strength of the composite materials depends on the volume fraction of the reinforcing phase [2]. In the examined materials, along with increasing volume of the reinforcing phase, bending strength  $R_g$  increases, intensively at the beginning and much slower at higher contents of reinforcement [15]. Reinforcing the matrix with preforms containing 10 to 30 vol.% of  $\text{Al}_2\text{O}_3$  ceramic particles results in increased strength of the composites by 8 to 10 % per each subsequent 10 vol.% of the reinforcement. The specimens containing 40 vol.% of the reinforcement show the highest bending strength reaching max. 433 MPa, which is ca. 90 MPa more in relation to the unreinforced matrix.

With increasing temperature, mechanical properties of the composites become clearly worse. The bending strengths at the applied test temperatures are shown in Fig. 9.

The largest drop of bending strength occurs for the specimens made of pure unreinforced matrix. Strength of the composite materials also decreases with increasing temperature. At lower test temperature, i.e. at 20 °C and 100 °C, the composites containing 10 vol. % of particles behave in a similar way as pure matrix, maintaining however ca. 25 to 30 MPa higher bending strength. At 200 and 300 °C, fractures of the specimens are still brittle with small plastic deformations.

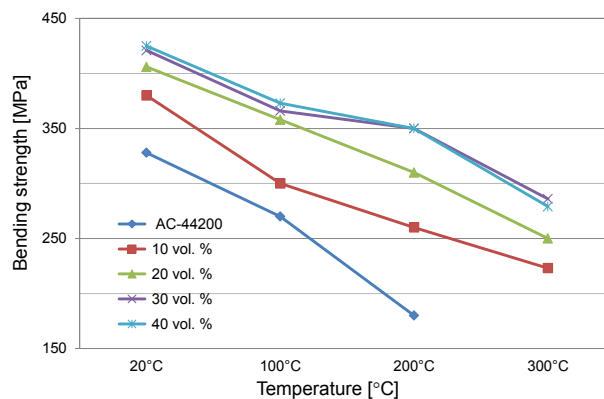


Fig. 9. Bending strength  $R_g$  of composite materials based on the aluminium alloy EN AC-44200 (AlSi12), reinforced with 10, 20, 30 and 40 vol.% of ceramic particles  $\text{Al}_2\text{O}_3$

Bending strength of the composites with 20 vol.% of particles decreases with increasing temperature in average by 50 MPa for the temperature increase of 100°C. During bend tests at ambient temperature, and at temperatures of 100, 200 and 300 °C, the specimens containing 30 and 40 vol.% of  $\text{Al}_2\text{O}_3$  particles behave in a similar way, with slightly higher strength values (by ca. 5 MPa) for the specimens with 40 vol.% of particles.

## 4. Summary and conclusions

1. Reinforcing the aluminium alloy EN AC-44200 (AlSi12) with  $\text{Al}_2\text{O}_3$  particles results in increasing of the bending strength in comparison to the unreinforced material. The highest bending strength of 410 to 432 MPa, tested at 20°C, is obtained for the material reinforced with 30 vol.% and 40 vol.% of particles,.
2. Increase of temperature from 20 °C to 300 °C results in significantly decreased bending strength of EN AC-44200 aluminium alloy based composite materials reinforced with  $\text{Al}_2\text{O}_3$  particles. It can be assumed that the bending strength decrease with increasing temperature in average 30 to 50 MPa per 100°C of temperature increase.
3. The specimens subjected to bending at ambient temperature and temperatures of 100, 200 and 300 °C show brittle fractures for the composites containing 30 and 40 vol.% of particles and mixed fractures with some plastic deformations for the composites containing 10 and 20 vol. % of particles.

4. Cracks in the composite materials propagate mainly along the interfaces between matrix and particles, although the cracking of ceramic particles were found as well. The particles at the fracture surfaces are well joined with the matrix by good mechanical and adhesive bonding and no falling-out of particles is observed.
5. With increasing temperature, breaking of the particles occurs as a result of increased plastic deformation of the matrix, mainly on tensioned sides of the specimens. The broken particles are more numerous in the materials containing 10 and 20 vol% of Al<sub>2</sub>O<sub>3</sub> particles, bent at 200 and 300 °C, where the matrix is more intensively deformed. Broken particles are observed in the places even at the distance of 60 μm away from the fracture surface. In these specimens, separation of the Al<sub>2</sub>O<sub>3</sub> particles from the matrix is also more often observed.
6. Propagation direction of the main fracture and development of minor cracks depend on the material defects like agglomerations of ceramic particles with residual porosity after incomplete and ineffective infiltration or agglomerations of hard and brittle unreacted silica that reduce strength of the material.

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