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Compressive Strength of EN AC-44200 Based Composite Materials Strengthened with α-Al_2O_3 Particles

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Abstract

The paper presents results of compressive strength investigations of EN AC-44200 based aluminum alloy composite materials reinforced with aluminum oxide particles at ambient and at temperatures of 100, 200 and 250°C. They were manufactured by squeeze casting of the porous preforms made of α-Al_2O_3 particles with liquid aluminum alloy EN AC-44200. The composite materials were reinforced with preforms characterized by the porosities of 90, 80, 70 and 60 vol. %, thus the alumina content in the composite materials was 10, 20, 30 and 40 vol.%. The results of the compressive strength of manufactured materials were presented and basing on the microscopic observations the effect of the volume content of strengthening alumina particles on the cracking mechanisms during compression at indicated temperatures were shown and discussed. The highest compressive strength of 470 MPa at ambient temperature showed composite materials strengthened with 40 vol.% of α-Al_2O_3 particles.

Keywords: Compressive strength, Composite materials, Aluminum oxide particles

1. Introduction

The elements of machines and equipment are subjected to severe and usually complex loads during operation. In the complex stress condition, apart from tensile, bending and shear stresses, also compression stresses are acting [1]. Increase of these stresses over the permissible strength for given materials may cause malfunction or damage, of not only these elements but effect as well on the functioning of the whole complex devices [1,2]. Nowadays, highly loaded machine parts are often made of metal alloy based composite materials reinforced with ceramic elements [3]. The composite materials are characterized by the high mechanical properties, providing the excellent strength properties, thus ensuring safe operation of machine parts made out of them [4-10]. Since the operation of machine elements occurs most frequently with their simultaneous heating, this paper contains research on the compression strength of composite materials during uniaxial compression tests and at the elevated temperatures.

The composite materials reinforced with ceramic particles show, that with the increase of the amount of the strengthening there is increase of hardness, wear resistance, and stiffness while reducing their ability to plastic strain [5-10]. Therefore, is a question of whether and to what extent, the ceramic strengthening particles will affect the inhibition of plastic deformation and provide an increase in compressive strength of materials not only at ambient temperatures, but also when are heated. In addition, analysis of strains of the composite specimen damaged during compression cycle with the different volumes of strengthening particles can provide the additional valuable information for the process of cold or hot plastic shaping of these materials.

2. Materials and methodology of the research

For manufacturing of composite materials the EN AC-44200 aluminum alloy exhibiting good casting fluidity, low shrinkage with simultaneous high mechanical properties was chosen. This alloy is particularly suitable for production of medium loaded construction of machines and equipment exploited in the severe conditions [7-11]. Table 1 shows the chemical composition of the alloy and in Fig. 1 an example of the cast microstructure.

Table 1.
Chemical composition of the matrix alloy

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

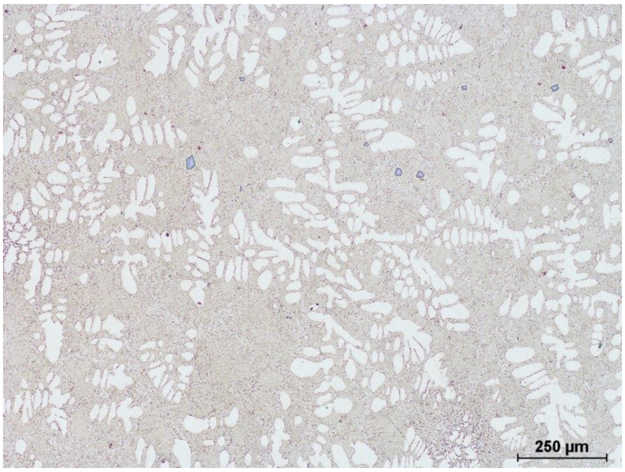

Fig. 1. Microstructure of the matrix alloy EN AC-44200

As the strengthening materials porous ceramic preforms made of α-Al_2O_3 particles were applied (specification given in Table 2).

Table 2.
Specification of α-Al_2O_3 particles

Al_2O_3 content: 99.7%						
Composition [wt.%]	SiO_2	Fe_2O_3	Na_2O	CaO	TiO_2	K_2O
	< 0.03	< 0.04	< 0.19	<0.01	<0.01	< 0.01
Density: 3.95 [g/cm^3]; diameter: 3÷6 [µm]						

The preforms were prepared on the basis of the bonding method with the aqueous solution of water - glass. Bonding between adjacent particles of Al_2O_3 can be described with the use of a general hardening formula (1) consisting of water - glass dehydration and switching from a viscoelastic condition to a solid phase [12]:

$$Na_2O \cdot nSiO_2 \cdot x\, H_2O + Q \rightarrow Na_2O \cdot nSiO_2, \quad (1)$$

where: n, x – stoichiometric coefficients, Q – heat

As the result of dehydration reaction there is formed a glassy layer of sodium silicate (Na_2O • $nSiO_2$), which forms the binding bridges between ceramic particles. The hardening reaction was carried out during the drying process in an atmosphere of CO_2 according to the reaction:

$$Na_2OnSiO_2\ x\ H_2O + CO_2 \rightarrow Na_2CO_3 + nSiO_2 + x\ H_2O + Q \quad (2)$$

As a result of a properly conducted drying process, preforms with the open porosity were obtained allowing further infiltration with liquid metal [8]. An exemplary structure of the preform is shown at Fig.2.

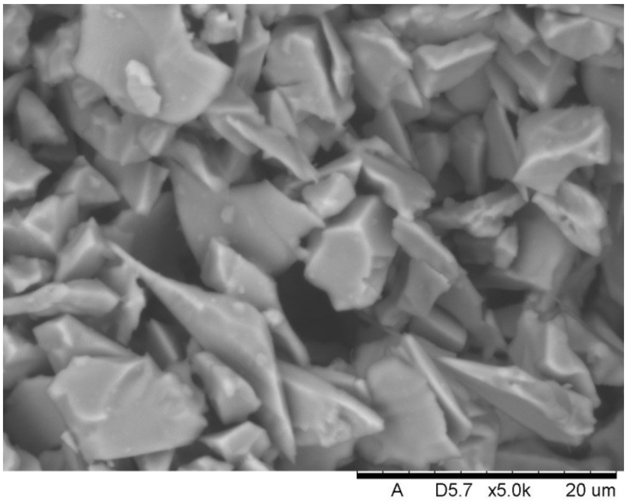

Fig. 2. Fracture of the preform made of the α-Al_2O_3 particles with the visible binding bridges

The process of preforms infiltration with EN AC-44200 liquid alloy was carried out applying a hydraulic press PHM-63 under pressure of P=90 to 100 MPa. The composite materials containing 10, 20, 30 and 40 vol. % of α-Al_2O_3 particles were investigated. An exemplary structure of composite material after infiltration is shown at Fig. 3. Due to specific distribution of alumina particles in the preforms, materials after infiltration are characterized by the structure with regions of the matrix containing almost no particles which were distributed between the areas with very densely distributed alumina particles.

The compressive strength test was performed applying the Instron 3369 testing machine. The specimens in the form of cylinders with a nominal height of h = 9.0 mm and a diameter of 6.0 mm were applied. The tests were carried out at ambient temperature of 20°C and at 100, 200 and 250°C. The specimens were compressed at a rate of 2 mm/min.

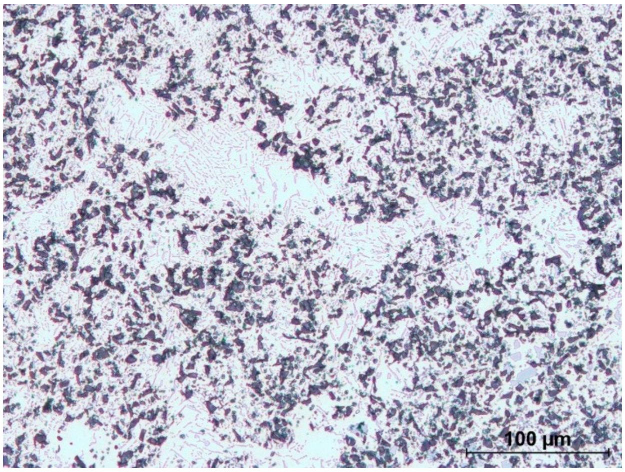

Fig. 3. Microstructure of the composite material EN AC-44200 - 20% vol. α-Al_2O_3 particles

3. Results and discussion

3.1. Compressive strength

The largest deformation of the specimens was observed for the specimens made of an unreinforced matrix material EN AC-44200. During compression at the temperatures of 100, 200 and 250°C a permanent specimen' swelling without the final cracking was observed. The typical shear fracture at 45° in the non-reinforced specimens subjected to compression at 20°C was present. Fig. 4 shows a general view of the deformed specimens after performed compression tests.

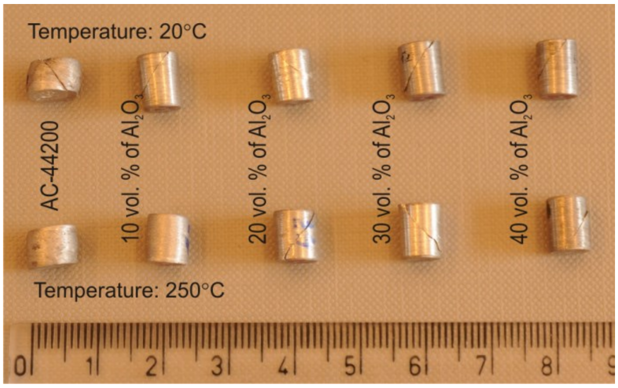

Fig. 4. Deformations of specimens after compression test at temperature: 20°C and 250°C

While testing, unreinforced materials EN AC-44200 showed the plastic properties and on the other hand the composite materials reinforced with particles showed the brittle character of cracking. Since for determining the strength of the plastic materials one should apply their compression yield strength and for brittle materials compressive strength due to the possibility of their good comparison in experiments; the maximum compressive stress for the plastic samples was taken and for the brittle samples stress of loosing of their consistency, or the presence of the shear fractures (Fig. 5).

Unreinforced specimens made from EN AC-44200 alloy during compression tests showed rapid swelling and with the increasing temperature of investigations, the maximum compressive strength significantly decreased. For instance at the ambient temperature, the maximum recorded stress was 285MPa and at the temperature of 250°C only 71MPa (Fig.5).

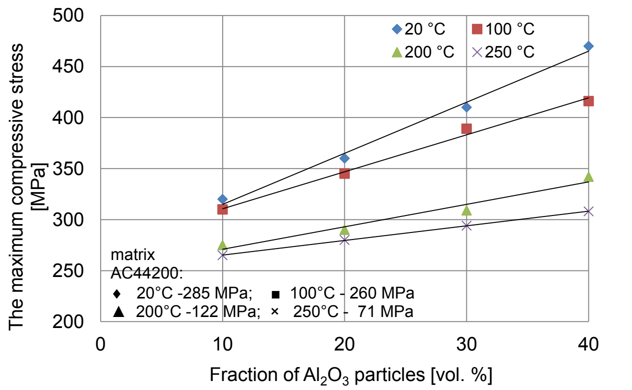

Fig. 5. Maximum compressive stress of EN AC-44200 alloy and composite materials

In comparison to the unreinforced matrix (at the temperature of 20°C), the strongest composite materials AC44200-40 vol.% Al_2O_3 shows more than 61% better strength. The increase in temperature to 250°C resulted in a significant decrease in strength, 4-fold for unreinforced alloy and only approx. 1.5-fold for composite materials. We can conclude that strengthening of the of EN AC-44200 alloy with ceramic α-Al_2O_3 particles improves especially the high temperature mechanical properties and at the same time limits the plastic flow of the material, in particular, at both low and elevated temperatures of the investigations.

In the manufactured composite materials, the stronger effect of strengthening with ceramic particles is visible at 20°C and 100°C. Increasing the temperature to 200, and 250°C effects on the matrix plasticization and therefore diminish an inhibiting effect of the deformation by the ceramic particles. With the increase of the particles content, there is a slow, almost linear increase in compressive strength, both at ambient and elevated temperatures.

3.2. Microstructure

The preliminary microscopic observations were performed at the unreinforced EN AC-44200 samples and the microstructure of specimen obtained from the intersection in a plane parallel to the direction of compressive force was analyzed (Fig.6). In the widest part of the swollen specimen the observations showed slight deformation in dendrites' arms and small cracks on the outer surface. Within the upper and the lower base of the sample there are strong deformations of the structure and in a middle part due to plastic deformation a dendritic structure was broken. In the zone of these deformations, the observations also confirm cracks of primary Si crystals subjected to tensile stress (Fig.6).

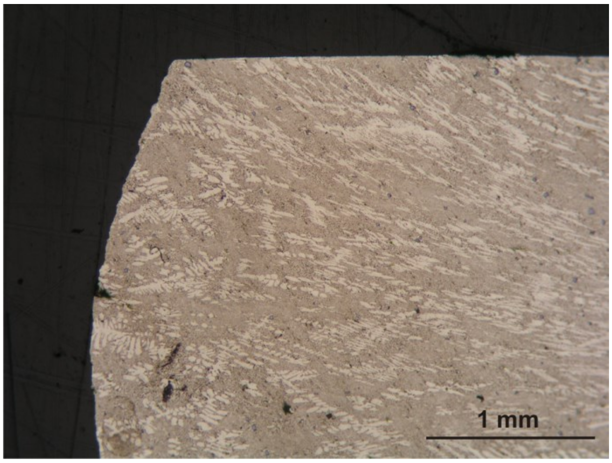

Fig. 6. The microstructure of an unreinforced material EN AC-4200 after deformation. Test temperature: 250°C

Composite materials containing ceramic alumina particles during compression at 20°C underwent the permanent destruction, showing brittle slip cracking in the plane at the approximately 45° to the axis of the sample. At the elevated temperatures, in EN AC-44200 materials with 10 vol.% of α-Al_2O_3 particles the crack was preceded by a slight swelling of the specimen. The specimens with 20, 30 and 40 vol.% of reinforcing particles showed the brittle cracking without the effect of swelling.

Regardless of the volume of reinforcing particles introduced to the matrix of composite materials, the privileged slip planes initiation were the regions with the smaller amount of the reinforcing particles (Fig. 7).

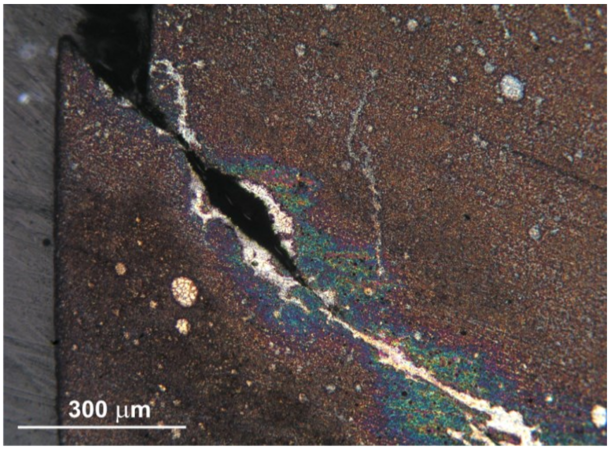

Fig. 7. The microstructure of the AC-44200-40 vol. %. Al_2O_3 with the slip crack after deformation. Test temperature: 150°C

The destruction of specimen progressed at the planes in which there were many of these areas. In addition, there is a clear tendency of a small changes in directions of cracking in the areas of matrix material rich in the ceramic particles, with bypassing obstacles (clusters of particles) (Fig. 8).

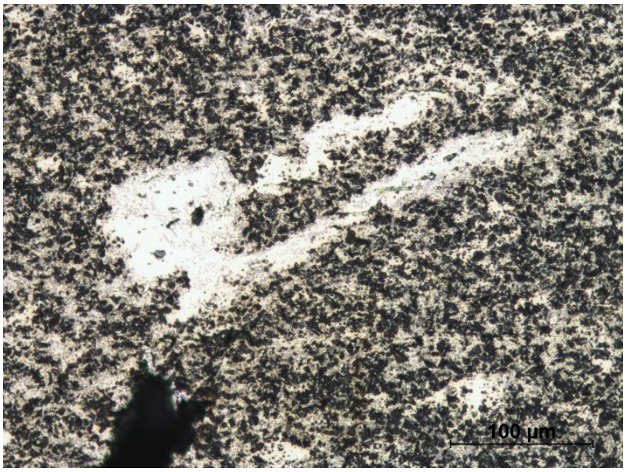

Fig. 8. The front of the slip crack and deformed regions without strengthening particles in the composite material EN AC-44200-20 vol. %. Al_2O_3. Test temperature: 250°C

In these areas (with smaller volume of the ceramic particles) there are also strong material deformations extending from oval shape for the non-deformed samples to longitudinal one for the strongly deformed samples. This tendency increases with the increasing test temperature.

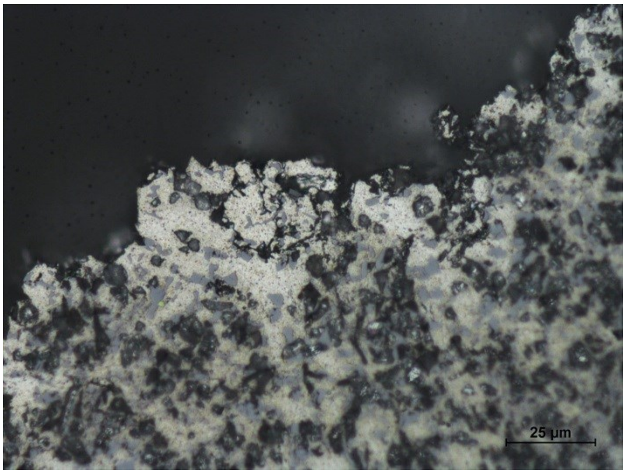

Fig. 9. The deformed composite EN AC-44200-20 vol. %.Al_2O_3 material in the vicinity of the slip crack. Test temperature: 20°C

There was ascertained the movement of ceramic particles with the plastically deformed matrix, although the particles inhibited and prevented to some extent, the deformation of aluminum alloy. No evidence of cracks in the particles resulted from the plastic flow in the matrix was ascertained. In the immediate vicinity of the main fracture, however, there are a few cracked particles presumably damaged as a result of a considerable friction forces created after the surface's cracking, causing also matrix's deformation (Fig. 9).

The presence near the cracks' surfaces of the precipitation of hard and during solidification unreacted brittle silica derived from the preforms binding also determines the direction of propagation of the crack. The crack normally propagates at the boundary of these precipitates as well as through them (Fig. 10).

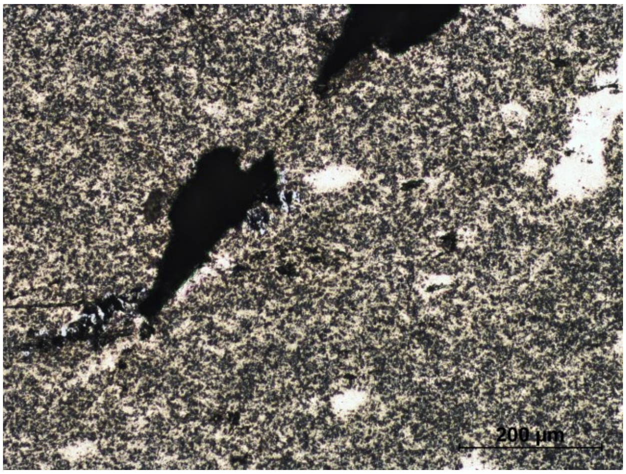

Fig. 10. The cracks of a composite material EN AC-44200-30 vol. %. Al_2O_3. Test temperature 150°C

Fracture surfaces after compressive loading were also observed with the use of a scanning microscope (SEM). The observed microstructures allows to come to conclusion that the initiation of the cracking process occurred primarily within the matrix material and propagated through the face boundaries of strengthening particles and the matrix (Fig. 11). In the materials compressed at 20°C, there is also a larger number of particles' cracks in the immediate vicinity of the fracture surface.

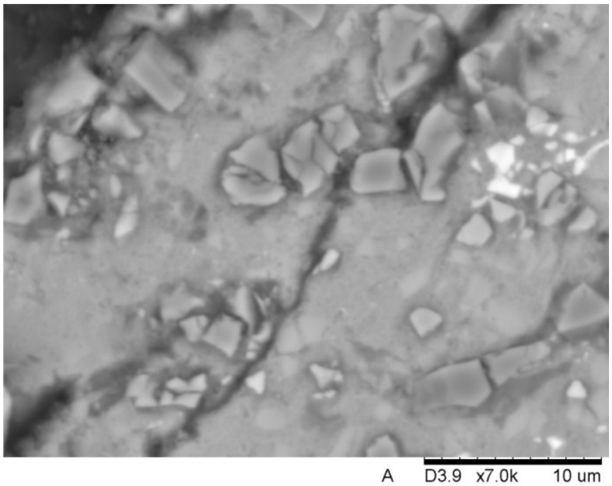

Fig. 11. SEM of a fracture of composite material EN AC-44200-10 vol.%. Al_2O_3. Test temperature: 20°C

In the places with high concentrations of ceramic particles there was a considerable number of material which was torn out. Furthermore, around the main crack, most often in the central part of the sample, there were microcracks and also delamination of the material. Stratification and isolation from the specimen underwent both the particles themselves and small fragments of matrix material with particles attached to it. The described phenomenon was mainly observed in the specimens with 30 and 40% of particles' volume (Fig. 12).

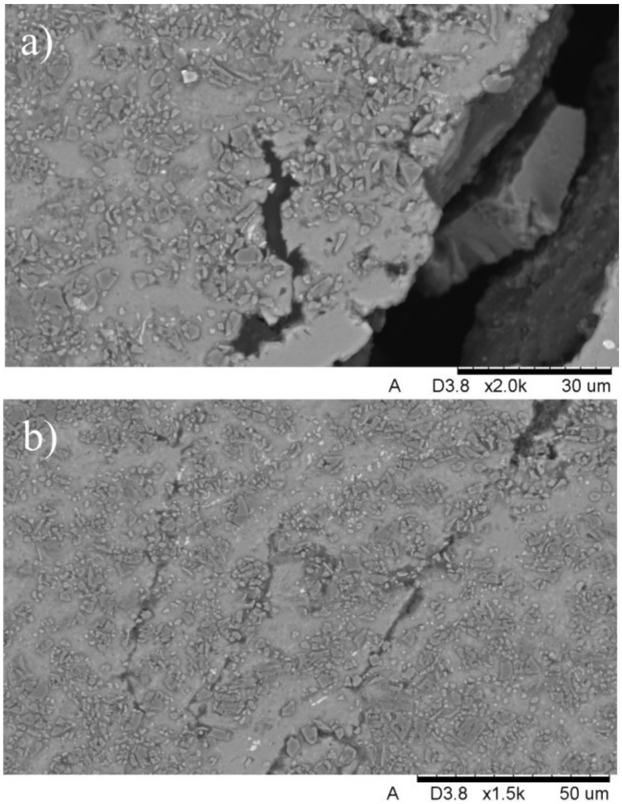

Fig. 12. SEM of a fracture of sample: a) material EN AC-44200-30 vol. %. Al_2O_3, b) material EN AC-44200-40 vol. %. Al_2O_3. Test temperature 20°C

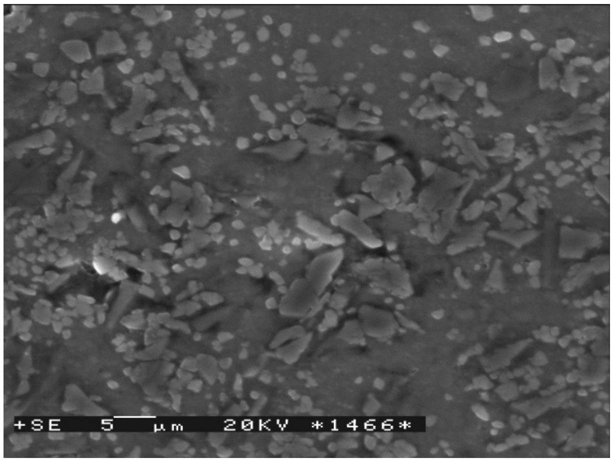

Fig. 13. SEM of the fracture with the delamination of EN AC-44200-20 vol. % of Al_2O_3 material in the mid-section of the sample. Test temperature 20°C

It should be also stressed that, in the case of occurrence in the material around the shear plane of porosity or bubbles, crack propagation could be caused in these places. Fig. 13 shows SEM of the material containing 20 vol. % of Al_2O_3 in the vicinity of main crack in which there was a residual porosity after incomplete infiltration affecting the course of crack.

In these areas, there is usually a poor connection of particles with the matrix material. As a result of the acting forces during compression of the sample there is detachment of the matrix from the strengthening particles and the movement of the particles with the plastically deformed matrix.

4. Summary and conclusions

The study of performed compression of aluminum composite materials and microscopic analysis of fractures of specimens allowed to draw the following conclusions:

1. Strengthening of EN AC-44200 aluminum alloy with ceramic α-Al_2O_3 particles increases their compressive strength, while decreasing the capacity to plastic deformation. At the ambient temperatures, the highest compressive strength of 470 MPa showed composite materials EN AC-44200-40% Al_2O_3. In relation to the unreinforced EN AC-44200 material they reached 61% higher strength at ambient temperature. Investigation of compressive strength at the temperature of 250°C indicated for the significant, approx. 35% reduction in the strength of EN AC-44200-40 vol. % of Al_2O_3 composite material.
2. The temperature change affects the way of crack creation. The composite materials containing 20, 30 and 40 vol. % of particles undergo brittle crack both at ambient and elevated temperatures.
3. The process of specimen' cracking of reinforced materials was mainly initiated within the matrix material or at the interface particles-matrix Less frequently the breakage and fragmentation of particles was observed.
4. The crack in the strengthened materials was of slip character in the direction of the largest shearing stresses at an angle of 45°C to the direction of the compressive forces was observed. The development of the main crack occurred mainly in places with a larger areas non-reinforced with the ceramic particles.
5. Initiation of the smaller cracks around the main crack is directly related to the volume of the strengthening phase. Typically they are formed in the areas of the greatest accumulation of strengthening phase, usually in composite materials with 30 and 40% of Al_2O_3.

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