

## The effect of $\alpha$ -alumina particles on the properties of EN AC-44200 Al alloy based composite materials

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### Materials

#### ABSTRACT

**Purpose:** The unreinforced EN AC-44200 aluminium alloy is characterized by the medium mechanical properties and the purpose of performed investigations was improvement of mechanical properties of this alloy by introducing stable ceramic  $\alpha$ -alumina particles.

**Design/methodology/approach:** The composite materials were manufactured by squeeze casting of porous ceramic preforms characterized by the open porosities of 90%, 80%, 70% and 60% with the liquid EN AC-44200 aluminum alloy. The composite materials containing 10 vol. %, 20 vol. %, 30 vol. % and 40 vol. % were manufactured and characterized by the homogeneous distribution of alumina particles in the matrix. On the base of microscopic investigations there was ascertained good bonding at the interface matrix/strengthening particles.

**Findings:** Manufacturing of porous ceramic preforms from alumina powders characterized by the desired open porosity was elaborated. After squeeze casting with liquid EN AC-44200 alloy there was noticed considerable increase of physical and mechanical properties: hardness HB increased from 82 HB for unreinforced alloy to 150 HB for material containing 40 vol. % of particles. There was noticed increase of tensile strength, bending strength and compression strength, although what is typical for composite materials, decrease of impact strength.

**Research limitations/implications:** There was noticed small rest porosity with decreasing porosity of the ceramic preforms. Further investigations on porosity removal basing on modification of production parameters are forseen.

**Practical implications:** Reinforcing of EN AC-44200 aluminum alloy with ceramic particles is effective taking into account increase of hardness and strength (tensile, bending, compression), although the relatively low impact strength can be restriction for the applications of these materials as the elements subjected to dynamic loads.

**Originality/value:** Manufactured materials can be applied as elements subjected to static loads and the relatively large specific strength allow to diminish the weight of elements applied in the construction of means of transportation.

**Keywords:** Composite materials; Strengthening particles; Aluminium matrix; Mechanical properties; Squeeze casting

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## 1. Introduction

Composite materials strengthened with ceramic particles are intensively developed according to their good mechanical and operating properties [1-3] and relatively good resistance to wear [4-5]. There are applied the cast and powder metallurgy methods of manufacturing of composite materials strengthened with ceramic particles. From the cast methods often squeeze casting of porous preforms made of ceramic powders ( $\text{Al}_2\text{O}_3$ , SiC) is applied [3-7] and mixing of ceramic strengthening particles in liquid metal and their casting (compocasting) [8]. According to the occurrence of the rest porosity in the composite materials strengthened with particles, after casting process plastic working in order to remove rest porosity is applied [9]. The powder metallurgical methods consist from mixing of matrix and strengthening powders, pressing, sintering and further plastic working in order to achieve small porosities [1,10-12]. Besides microparticles good strengthening effects is obtained applying the halloysite nanotubes [13], nanoparticles of SiC [14] and  $\text{Al}_2\text{O}_3$  [15]. Generally the composite materials strengthened with ceramic particles can be further plastic worked what results in very good mechanical and development properties contrary to materials strengthened with ceramic fibres which cannot be plastic worked. Elements made from composite materials according to their good mechanical properties are characterized by good specific strength given in km understood as the relation of chosen strength (tensile, bending, compression) in  $\text{MN/m}^2$  to the specific gravity in  $\text{N/m}^3$ . This parameter is very important for the applications of composite materials in construction of means of transportation, especially aircrafts and ground vehicles [16].

## 2. Work methodology and materials

The composite materials were manufactured by squeeze casting of porous preforms made of alumina ceramic particles shown at the Fig.1. Ceramic particles had irregular shape and dimensions in the range of 3-5  $\mu\text{m}$ . There were manufactured porous preforms characterized by the open porosities of 90%, 80%, 70% and 60%. The manufacturing process of porous preforms consisted from preparation of mixture of alumina particles, binder in water solution and pores forming agent. The prepared slurry was poured into the mould shaping the preform and the mould was heated in order to remove the excess of water. During heating the bridges between ceramic particles were formed. The preforms were then fired at the temperature of  $1000^\circ\text{C}$  in order to form stable and strong bridges between ceramic particles keeping at the same time the open porosity of the preform.

After manufacturing of porous preforms permeability was examined in order to check the possibility of infiltration of preforms with the molten aluminium alloy [17]. The largest permeability of  $19.1 \text{ m}^2/\text{Pa s}$  was ascertained for preforms characterized by the largest porosity of 90% and permeability for the preform characterized by the smallest porosity of 60% was of  $3.0 \text{ m}^2/\text{Pa s}$ . On the base of performed measurements it was ascertained that these permeabilities are sufficient for the infiltration of ceramic preforms with liquid aluminium alloy.

Besides permeability the relative good mechanical properties are needed, taking into account the large forces acting on the

ceramic preform during squeeze casting process. The mechanical properties were the largest for preforms characterized by smallest porosities and the bending strength for the manufactured preforms varied from 1.7-7.0 MPa, shear strength varied from 0.3-4.2 MPa and compression strength from 1.0-11.7 MPa what was sufficient to keep the preform shape during squeeze casting.

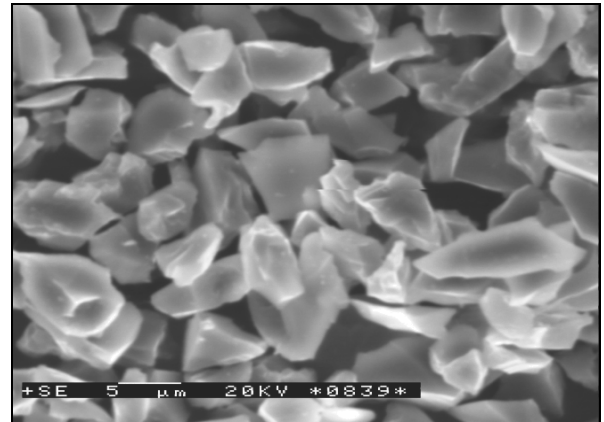


Fig. 1. Alumina particles of 3-5  $\mu\text{m}$  applied for manufacturing of porous ceramic preforms

The squeeze casting process was performed applying the mould at the Foundry Chair of the Institute of Mechanical Engineering and Automation which is shown with the ceramic preform before closing (Fig. 2).



Fig. 2. Mould for squeeze casting with fibre preform before closing

The EN AC-44200 aluminium alloy was applied for the squeeze casting process and its chemical composition is shown at the Table 1. The physical and mechanical properties of unreinforced EN AC-44200 alloy are given at the Figs. 4, 6, 8, 9 and 12.

Table 1.

Chemical composition of EN AC-44200 cast aluminium alloy					
Alloy	Al	Si	Fe	Cu	Mn
EN AC-44200	Balance	10.5-13.5	0.55	0.05	0.35

The squeeze casting was performed applying the parameters shown in Table 2. After squeeze casting process the volume contents of ceramic  $\alpha$ -alumina particles were of 10 vol.%, 20 vol.%, 30 vol.% and 40 vol.%. Besides temperatures of tools the especially important is temperature of liquid EN AC-44200 alloy and the infiltration pressure. Application of too small infiltration parameters can result in not full infiltration of the preforms and their damage.

Table 2. Production parameters of composite materials

Squeeze casting parameter	Quantity
Infiltration pressure	80 - 100 MPa
Temperature of EN AC-44200	720 - 740°C,
Temperature of ceramic preform	480 - 520°C,
Temperature of the mold	200 - 300°C,
Temperature of the punch	150 - 200°C.

The metallographic structure of manufactured composite materials was shown at the Fig. 3 and indicates for the homogeneous distribution of ceramic alumina particles in the EN AC-44200 matrix. SEM observations revealed relatively good bonding at the interface ceramic particles-aluminium alloy matrix what is important for the achievement of good mechanical and operational properties. The investigations of hardness HB, tensile strength, bending strength, compression strength and impact strength were performed.

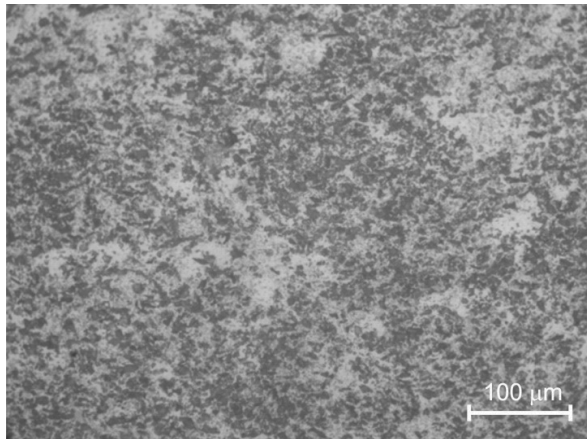


Fig. 3. Metallographic structure of composite materials on the base of EN AC-44200 alloy strengthened with 30 vol. % alumina particles

### 3. Results and discussion

The ceramic  $\alpha$ -alumina particles in the matrix affected on the linear increase of HB hardness and for particles content of 10 vol.% hardness was of 84 HB and for composite material containing 40 vol.% of particles hardness was of 150 HB (Fig. 4).

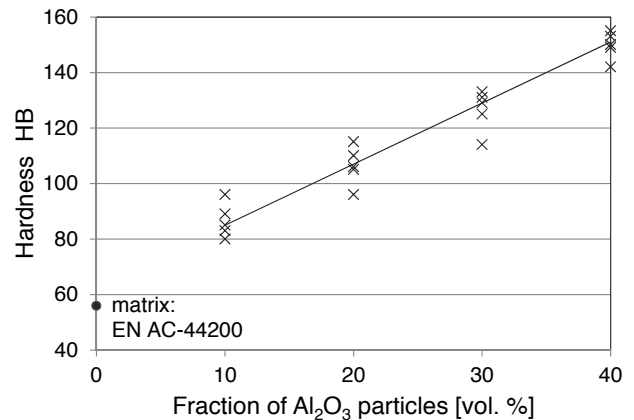


Fig. 4. Hardness HB of composite materials

Tensile strength was investigated at the round samples of diameter of 6.0 mm and measurement length of  $l_0=30$  mm. The tensile fractures were found at the accidental places of the measuring length of the samples and no regularity in this matter was established (Fig. 5). The results of tensile strength investigations are shown at Fig.6. Samples with 10 vol.% of alumina particles has shown the largest tensile strength of 248 MPa which was 61% better than tensile strength of unreinforced EN AC-44200 aluminium alloy. Increasing of the volume content of ceramic particles in the matrix effected on the decreasing of tensile strength and for materials containing 40 vol.% of ceramic particles it was of 200 MPa but still 29% better than of unreinforced alloy. The reason of such effect is connected with the increasing porosity in materials containing larger amounts of particles, what can additionally influence on the poor adhesion at the interface metal/ceramic particles.

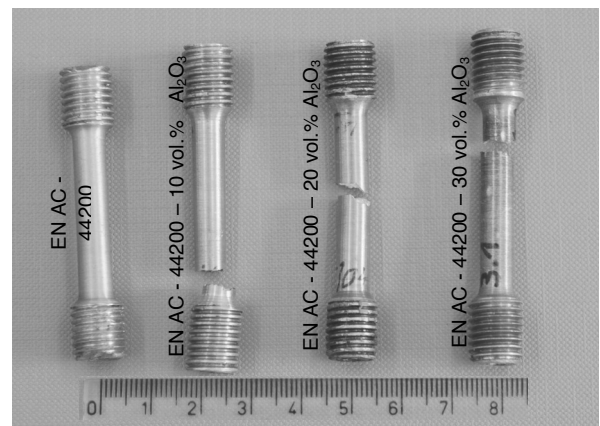


Fig. 5. Tensile samples made of EN AC-44200 unreinforced alloy and from composite materials containing 10 vol.%, 20 vol.% and 30 vol.% of  $\alpha$ -alumina particles

The observations of tensile fractures of samples revealed limited plastic flow of materials at the region of tensile fracture (Fig. 7a) and the relative good bonding at the interface (Fig. 7b).

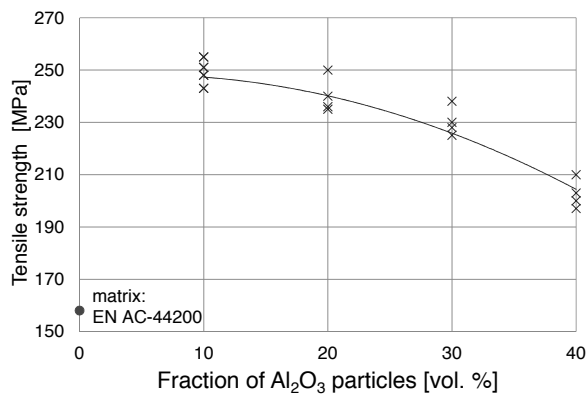


Fig. 6. Tensile strength of composite materials

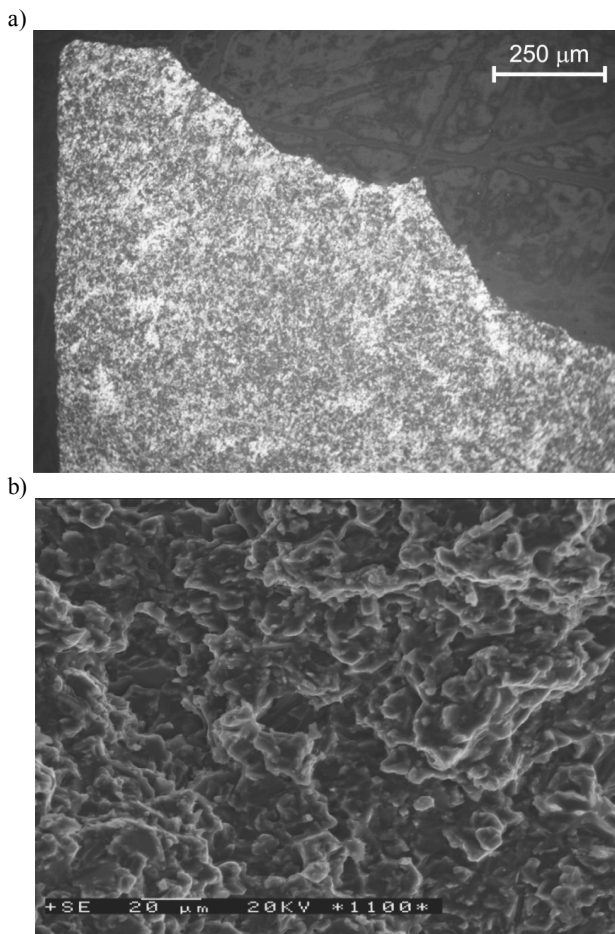


Fig. 7. Fractures of composite material a) EN AC-44200-30 vol.% of alumina particles in the plane parallel to tensile force b) AC-44200 - 20 vol.% of ceramic alumina particles at the fracture plane

The calculations of specific strength as the relation of tensile strength in  $\text{MN/m}^2$  and specific gravity in  $\text{N/m}^3$  are given in  $\text{km}$  and are given at the Table 3. They indicate that specific tensile strength of unreinforced EN AC-44200 aluminium alloy is 5.98

$\text{km}$  and the composite material containing 10 vol.% of  $\alpha$ -alumina particles is characterized by the specific tensile strength of 9.02  $\text{km}$ . It means the increasing of specific tensile strength of 50.8% in relation to the unreinforced EN AC-44200 aluminium alloy. All specific strengths were larger than specific strength of unreinforced aluminium alloy. Larger specific strength makes possible manufacturing of the elements from composite materials which can be relatively lighter than parts made of unreinforced alloy.

Table 3.

Specific strength of manufactured composite materials on the base of EN AC-44200 aluminium alloy

Materials	Specific strength in [km]
EN AC-44200 aluminium alloy not reinforced	5.98
EN AC-44200 aluminium alloy – 10 vol.% of alumina particles	9.02
EN AC-44200 aluminium alloy – 20 vol.% of alumina particles	8.42
EN AC-44200 aluminium alloy – 30 vol.% of alumina particles	7.61
EN AC-44200 aluminium alloy – 40 vol.% of alumina particles	6.60

L. Ceschini et al. [9] investigated the tensile properties of composite materials based on AA 2618 strengthened with 20 vol.% of alumina particles. They ascertained that after squeeze casting process and applied T6 treatment the tensile strength was of 361 MPa. Taking into account that the tensile strength of unreinforced AA2618 T6 is 440 MPa it means the worsening of the tensile strength. On the other hand the application of forging improved the tensile strength to 454 MPa and the improvement can be explained by the breaking of particle clusters induced by the flow of matrix aluminium alloy during plastic working which can be realized by forging, hot extrusion and hot rolling [9]. The other reason improving the mechanical properties are according to [9] “synergistic effects” like grains refinement, reduction of porosity and according to [18] dissolution of brittle compounds.

The investigations of bending strength showed the effect of alumina particles content on this property and taking into account that the unreinforced matrix is characterized by the bending strength of 340 MPa the addition of 10 vol.% of ceramic alumina particles results in increase of this property to 380 MPa (Fig. 8). The maximum bending strength of 420 MPa showed samples with 30 and 40 vol.% of alumina particles.

The investigations of bending strength were performed by S.N. Chou at al. [5] on composite materials manufactured by squeeze casting with aluminium A356 alloy (7.0Si-0.3Mg-0.2Fe-0.10Zn) of porous preforms characterized by very small porosities of 5 vol.%, 10 vol.%, 20 vol.%, 30 vol.% and 40 vol.%. They ascertained that the bending strength increase with increasing A356 alloy content until 10 vol. % reaching 480 MPa and for larger contents of aluminium alloy the bending strength is smaller reaching 450 MPa for 40 vol.% of A356 aluminium alloy.

Further investigations showed the increase of compressive strength with the increasing volume content of ceramic alumina particles in the matrix (Fig. 9). Taking into account that the compressive strength of unreinforced EN AC-44200 aluminium alloy is 280 MPa the strengthening with 10 vol.% of particles

increase the compressive strength to 330 MPa. Logically the further increase of compressive strength is connected with the increased blocking of sliding planes by the ceramic  $\alpha$ -alumina particles so the compressive strength of composite materials containing 10 vol.% of particles is 17.8% larger than of unreinforced matrix and the maximum compressive strength of 475 MPa is 69.6% larger than of unreinforced matrix alloy.

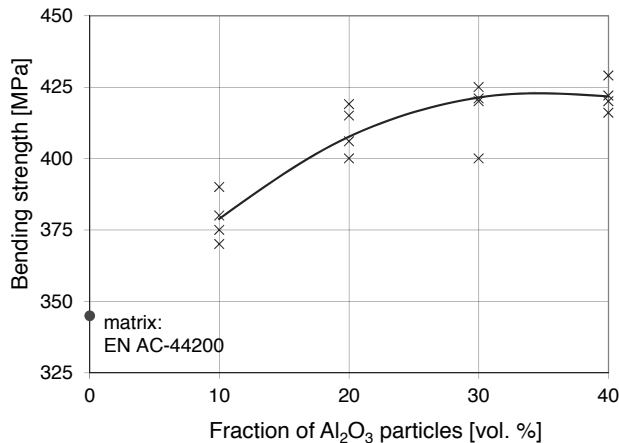


Fig. 8. Bending strength of composite materials

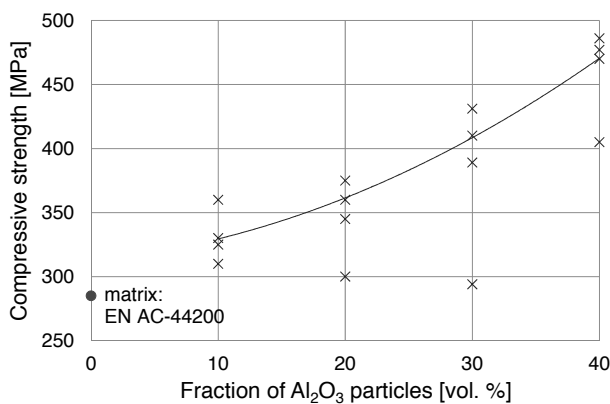


Fig. 9. Compressive strength of composite materials

All samples containing strengthening particles after investigations of compression strength showed the brittle fractures, which started especially at the materials defects, like clusters of ceramic particles shown at the Fig. 10. It is remarkable that the fracture created by compression force do not pass through the regions with the smaller content of ceramic particles, characterized by the larger plasticity than the reinforced matrix, what is visible at the Fig. 10. The observations of the fracture plane after compression test performed with the help of SEM revealed fraction surface with alumina particles characterized by the relative good bonding at the matrix/particles interfaces. In some places the sliding traces of ceramic particles at the friction surface are visible (Fig. 11).

The impact strength of composite materials was strongly affected by the ceramic alumina particles and the largest impact

strength of  $6.2 \text{ kJ/m}^2$  was characterized by the unreinforced samples made from EN AC-44200 alloy and strengthening of matrix with ceramic particles depressed the impact strength (Fig. 12).

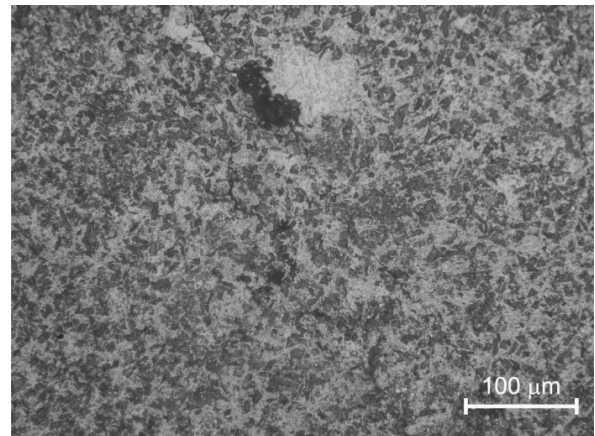


Fig. 10. Structure of fracture region in samples after compression test

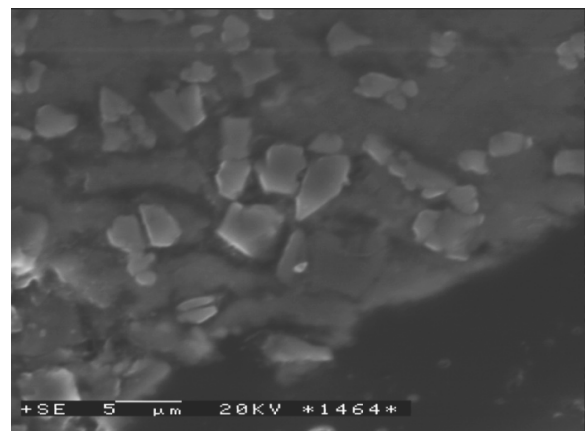


Fig. 11. SEM of fracture of composite materials AC-44200-10 vol.% of  $\text{Al}_2\text{O}_3$  particles after compression tests

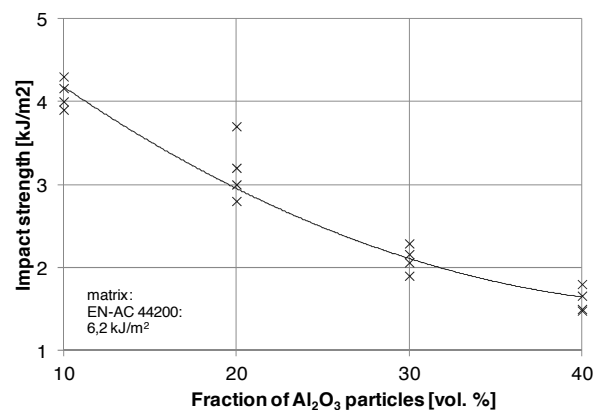


Fig. 12. Impact strength of composite materials

The impact strength of composite materials containing larger amounts of particles was much smaller than of unreinforced matrix and for composite materials containing 40 vol.% of particles it decreased to 1.7 kJ/m<sup>2</sup> what is only 27.4% of the impact strength of unreinforced matrix

Generally metal alloys are characterized by the relatively high fracture toughness  $K_{IC}$  which for Cu alloys are of 12.0 MPa m<sup>1/2</sup>, and for Al alloys of 29 MPa m<sup>1/2</sup>. Ceramic particles in the matrix effect on the lowering of fracture toughness which for composite materials on Al alloy strengthened with 30 vol.% of alumina particles is 6.5 MPa m<sup>1/2</sup> [19]. Generally cracks during investigations of the impact strength propagated at the interfaces strengthening particles / aluminium matrix effecting in the relatively low impact strength.

#### 4. Conclusions

1. Squeeze casting applying the pressure of 100 MPa of porous ceramic preforms made of  $\alpha$ -alumina particles of porosities 60%, 70%, 80% and 90% results in production of composite materials characterized by low rest porosity and good bonding at the interface ceramic strengthening- EN AC-44200 aluminium alloy.
2. Hardness of composite materials increased linearly with increasing alumina particle volume content in the matrix.
3. The tensile strength is strongly affected by the ceramic particle content in the matrix and the maximum tensile strength was achieved for the composite materials EN AC-44200-10 vol.% of  $\alpha$ -alumina particles. The rest porosity in materials containing larger volume contents of particles affected on the lowering of tensile strength.
4. Bending strength and compression strength increased with increasing volume content of alumina particles and the maximum of these strengths were reached for 40 vol. % of alumina particles in the matrix.
5. Impact strength of all composite materials was lower than of unreinforced alloy according to the crack propagation at the interfaces. Larger surface of interfaces in composite materials containing larger volume contents of particles affected on the lower impact strength.

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