Impact Strength of Composite Materials Based on EN AC-44200 Matrix Reinforced with Al₂O₃ Particles

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Received 19.04.2017; accepted in revised form 07.06.2017

Abstract

The paper presents the results of research of impact strength of aluminum alloy EN AC-44200 based composite materials reinforced with alumina particles. The research was carried out applying the materials produced by the pressure infiltration method of ceramic preforms made of Al₂O₃ particles of 3-6μm with the liquid EN AC-44200 Al alloy. The research was aimed at determining the composite resistance to dynamic loads, taking into account the volume of reinforcing particles (from 10 to 40% by volume) at an ambient of 23°C and at elevated temperatures to a maximum of 300°C. The results of this study were referred to the unreinforced matrix EN AC-44200 and to its hardness and tensile strength. Based on microscopic studies, an analysis and description of crack mechanics of the tested materials were performed. Structural analysis of a fracture surface, material structures under the crack surfaces of the matrix and cracking of the reinforcing particles were performed.

Keywords: Composites, Aluminum oxide particles, Impact strength, Tensile strength, Squeeze casting

1. Introduction

Strengthening of the aluminum, magnesium or copper alloys with particles, fibers or other types of ceramic reinforcement usually results in increased mechanical properties [1-5]. This has led to the research activity in order to achieve the best possible results in the strengthening of materials [6-9]. Real and critical issue for wide applications of composite materials seems to be maintaining the relative high strength properties when operating at ambient temperature or at elevated temperatures [10-13]. These materials are characterized by the high mechanical properties such as tensile, bending or compression strength, but on the other hand they are not characterized by the large impact strength. These issues have been investigated by researchers using composite materials with different matrices and with various contents of the reinforcing elements [14-18]. Relatively few, however, can be found in literature on impact strengths of metallic composite materials at elevated temperatures, which may be essential during their use. Because of this, the purpose of this work was to investigate the impact strength of composite materials with aluminum alloy EN AC-44200 matrix reinforced with Al₂O₃ particles in the temperature range of 20°C to 300°C.
2. Materials and experimental methods

Hardness, impact strength and tensile strength of aluminum alloy EN AC-44200-based composite materials reinforced with Al₂O₃ ceramic particles were determined. Materials were made produced applying the squeeze casting method. The process of materials’ production consisted in the first stage of producing and then fixing in a proper place of a casting mold a porous preform and its infiltration with preheated to 720°C liquid EN AC-44200 Al alloy. The infiltration process was carried out on a hydraulic press at a pressure of 90+100MPa.

Composite reinforcements were preforms made of Al₂O₃ particles with a density of 3.95 g/cm³ and a particle size of 3μm±6μm. Particle bindings were formed basing on the technology described in [5, 9] based on the use of hydrated glass water solution Na₂O • nSiO₂ • xH₂O (n, x - stoichiometric coefficients) hardened with CO₂.

An exemplary preform structure is illustrated in Fig. 1 with a designated bridge connecting the particles, chemical composition of which is given in Table 1.

![bonding bridge](image)

**Fig. 1. Preform structure made of Al₂O₃ particles**

**Table 1. Summary results EDS**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass %</th>
<th>Atomic %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>43.831</td>
<td>35.918</td>
</tr>
<tr>
<td>Oxygen</td>
<td>31.650</td>
<td>43.740</td>
</tr>
<tr>
<td>Sodium</td>
<td>5.951</td>
<td>5.724</td>
</tr>
<tr>
<td>Silicon</td>
<td>18.568</td>
<td>14.618</td>
</tr>
</tbody>
</table>

EN AC-44200 alloy having sufficiently high castability was chosen for a matrix of composite materials, which is a condition of the effective preforms’ impregnation with liquid metal in the infiltration process, and also has an effect on reducing porosity of composite castings. This alloy, in addition to its low density (2.65g/cm³), has high mechanical properties, which is why it is frequently used in the construction of machine parts and appliances. The EN AC-44200 alloy specifications are given in Table 2.

![Microstructure](image)

**Fig. 2. Microstructure of a composite material EN AC-44200-20% vol. Al₂O₃ particles**

**Table 2. Chemical composition of EN AC-44200 matrix material**

<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>Matrix</td>
<td>10.5-13.0</td>
<td>0.55</td>
<td>0.05</td>
<td>0.35</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>AC-44200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Al - remainder

As a result of a squeeze casting process, composite materials have been obtained with the structure of alternately arranged matrix’s fields with fields having an increased amount of ceramic particles. Such a structure results from the method of preforms’ production based on the use of a filler that is removed by firing. An exemplary material structure with 20% vol. Al₂O₃ particles is shown in Figure 2.

Composite samples taken from castings containing respectively 10, 20, 30 and 40% vol. of Al₂O₃ reinforcing particles were tested. For comparative purposes, the research was also carried out on the EN AC-44200 materials unreinforced with particles.

Impact strength determination was carried out with the use of the Charpy method in accordance with PN-EN ISO 148-1: 2010. The test was performed on standardized samples without a notch in the shape of a cuboid with dimensions: l = 50mm, h = 4mm, b = 6mm at ambient temperature of 23°C and also at temperatures of: 100, 200 and 300°C.

The tensile strength test was performed on an INSTRON machine based on PN-EN 10002-1: 2004 Standard. Tensile rate was of 2 mm/min. Samples of nominal diameter of d = 6.0 mm and measuring part length lₚ = 30.0 mm were used. The tensile test was performed at 23°C and at 300°C.

Hardness tests were carried out with the use of Brinell method using a 2.5 mm diameter steel ball under 625N load.

Scanning microscopy was performed with the use of the Hitachi TM-3000 scanning microscope and the microstructure study with the use of the Nikon Eclipse MA200 light microscope.
3. Results and discussion

3.1 Hardness and impact strength

Hardness dependence on the amount of reinforcing particles is shown in Fig. 3.

![Graph showing hardness vs. fraction of Al2O3 particles]

Fig. 3. Brinell hardness HBW/2.5/625N EN AC-44200 - Al2O3 particles

Strengthening of EN AC-44200 matrix with 10 vol.% of Al2O3 ceramic particles results in an increase in HBW hardness by about 30-40%. As a result of increasing the volume of reinforcement of every 10% up to 40% volume an approximately linear increase in hardness is reached. Material hardness increases by about 20% per 10% volume of particles. The highest average hardness of 158 HBW are characterized by materials with a particle volume of 40%, which is approximately 3 times higher than that of an unreinforced material.

![Graph showing impact strength vs. temperature]

Fig. 4. Impact strength of composite materials AC44200-Al2O3

In the Charpy’s impact test, the work required to break and to create a fracture surface of the sample was determined. The average impact values [kJ/m²] in the temperature range of 23-300°C of EN AC-44200 aluminum alloy and composite materials are shown in Figure 4. The tests confirmed the effect of both the amount of reinforcing particles and temperature on the impact strength.

The highest impact strength showed the unreinforced alloy EN AC-44200, which impact strength at the ambient temperature was 6.2 kJ/m². Determination of the impact strength at the test temperature of 100°C showed more than double dynamic impact strength caused by the increase of the plasticity of the matrix. At the temperature of 200°C, the impact strength still increased but only by another 10-15%. The lack of a measuring point at 300°C results from increased capability of samples for plastic deformation and dragging the samples through a handle support.

Composite materials with 10% vol. of Al2O3 particles show about 30% less impact strength at 23°C than the EN AC-44200 unreinforced matrix. Increased volume of ceramic particles to 40% vol. reduces impact strength up to 60%. At elevated temperatures due to the presence of particles in the matrix, composite materials show a dominant brittle type of destruction. However, a noticeable increase in the impact strength value along with the increase in temperature may indicate an increase in matrix’s role in load transfer. A similar relationship was observed in the work of [17] on composites produced on the basis of 6061 alloy with 20% Al2O3 content and in the work [18] on the basis of 5083 Al alloy reinforced with the SiC particles.

The smallest impact strength showed composite materials containing 40% vol. of Al2O3 particles keeping a constant value of the impact strength of approximately 2 kJ/m² over the entire temperature range of investigations.

3.2. Tensile strength

The performed research confirmed that reinforcement with the particles in a volume of 10 to 40 vol.% leads to an increase in tensile strength both at ambient temperature and at the temperature of 300°C (Table 3).

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Rm [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>23°C</td>
</tr>
<tr>
<td>Material</td>
<td>min</td>
</tr>
<tr>
<td>AC44200</td>
<td>150</td>
</tr>
<tr>
<td>AC44200+10%Al2O3</td>
<td>245</td>
</tr>
<tr>
<td>AC44200+20%Al2O3</td>
<td>240</td>
</tr>
<tr>
<td>AC44200+30%Al2O3</td>
<td>227</td>
</tr>
<tr>
<td>AC44200+40%Al2O3</td>
<td>198</td>
</tr>
</tbody>
</table>

The smallest tensile strength at all tested temperatures showed unreinforced Al alloy EN AC-44200. At the temperature of 300°C the samples showed the significant plastic deformation for which the yield strength Rm0.2 was 78 to 88 MPa.

Investigations of composite materials at the temperature of 23°C have shown that the highest tensile strength of 258 MPa is reached for composite material containing 10 vol.% of Al2O3 particles. For unreinforced materials this value is about 40% lower. Not much lower, because of only about 2% lower tensile strength show materials reinforced with 20% vol. of alumina particles. As the volume of particles in the composite materials increases, the strength gradually decreases, but it retains
significantly higher values than the pure unreinforced matrix. The smallest strength of 198 ÷ 210MPa showed composite materials on EN AC-44200 matrix strengthened with 40% vol. of alumina particles. With regard to the unreinforced material EN AC-44200 for which Rm is 150MPa it is about 25% higher.

Studies of the tensile strengths conducted at elevated temperatures have shown that the temperature value strongly influences a change in the tensile strength value Rm. At 300°C, the highest strength Rm values showed samples with 20% vol. of Al2O3 particles reaching 158MPa. So when the materials are heated from 23°C to 300°C, the strength decreases by about 40%.

3.3. Microstructure

Scanning Electron Microscopy observations of cracks and microstructure studies performed under the surface of cracks were conducted by analyzing formation and development of cracking during the dynamic impact test.

Fig. 5 shows the cracks of an unreinforced matrix alloy EN AC-44200 resulting from a test run at 23°C. The fracture is characterized by a plastic brittle crack with slight relatively plastic α-phase and visible numerous broken and cracked Si crystals. The observations confirm dendrites break and their detachment from eutectic.

In the composite materials reinforced with ceramic particles tested at ambient temperature, cracks are of typically brittle character with the small areas of plastic deformation occurring mainly in materials containing 10% vol. of Al2O3 particles. Impact destruction of areas with increased matrix volume results in a tendency rather to propagate cracking across a boundary of these areas than in areas containing ceramic particles, (Figure 6).

The additional cracks are usually present in materials with larger matrix volumes, i.e. in composites with smaller amount of reinforcing particles of 10 vol.% and 20 vol.%. Ceramic Al2O3 particles are firmly embedded in the matrix material on the edges of the cracks. Sometimes smaller pieces of the material are released from the edge, also containing reinforcing elements in their volume.
SEM studies of surface cracks confirm the presence of strongly-embedded reinforcing particles in the matrix. In rare cases, especially in composites with 30 and 40% vol. of particles, the matrix, as a result of dynamic impact and stretching forces, undergoes debondings from the particles’ surface. Debondings are more frequently observed in composites subjected to impact loads at 23°C. Observations also confirm at the crack surface the presence of cracked primary Si crystals of aluminum matrix (Figure 9 and Table 4).

At the higher temperatures, and in particular at 300°C, Al₂O₃ particles are less likely to break and the crack’s development is mainly on the matrix material. Observations confirm the presence of numerous matrix fragments stretched in the direction of tensile stresses at the particles’ surfaces adhering thereto (Figure 10).

**4. Summary and Conclusions**

1. Composite materials reinforced with particles show significantly less dynamic impact resistance in comparison with unreinforced matrix at both ambient and elevated temperatures up to 300°C, while retaining high hardness and tensile strength. Strengthening of composite materials with 10% vol. of Al₂O₃ particles reduces impact strength by about 30% and in composite materials with 40% volume up to 60%. As temperature increases from 23°C to 300°C, there is an approximately linear increase in the impact strength value. At the temperature of 300°C composite materials with 10% vol. of particles show the largest impact strength of 6.0 kJ/m² comparing with the 2.0 kJ/m² for materials containing 40 vol.% of particles. This confirms the increased, relative to the particle's share, role of the matrix in the transfer of dynamic loads at the higher temperatures.

2. Materials containing 40% vol. of Al₂O₃ particles have the largest, roughly three times greater than the unreinforced alloy EN 44200 hardness which is 158HBW/2.5/625N. On the other hand, the highest tensile strength of 258MPa at 23°C and 158MPa at 300°C show composite materials with 10% vol. of Al₂O₃ particles.

3. Unlike unreinforced matrix material, during the impact test at 23°C, composite materials show brittle fractures. Cracks propagation develop both through the matrix material, particles and matrix-particle interfaces.

4. At the elevated temperatures (mainly at 300°C), the cracks propagate mainly inside the matrix’s material. Strong
adhesive bonding of the matrix to the ceramic particles confirms fragments of matrix adhering at the surface of the ceramic particles.

Acknowledgment

The results presented in this paper have been obtained within the project “KomCerMet” (contract no. POIG.01.03.01-00-013/08 with the Polish Ministry of Science and Higher Education, Warsaw) in the framework of the Innovative Economy Operational Programme (POIG) 2007-2013.

References