www.czasopisma.pan.pl PAN www.journals.pan.pl
POLSKA AKADEMIA NAUK

ARCHIVES of FOUNDRY ENGINEERING

DOI: 10.1515/afe-2017-0094

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

DE GRUYTER OPEN

ISSN (2299-2944)
Volume 17
Issue 3/2017

73 – 78

Impact Strength of Composite Materials Based on EN AC-44200 Matrix Reinforced with Al_2O_3 Particles

A. Kurzawa *, J.W. Kaczmar
Wrocław University of Technology, Faculty of Mechanical Engineering,
Chair of Foundry Engineering, Plastics and Automation
Ul. Ignacego Łukasiewicza 5, 50-371 Wrocław, Poland
*Corresponding author. E-mail address: adam.kurzawa@pwr.edu.pl)

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 Al_2O_3 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 Al_2O_3 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 Al_2O_3 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 Al_2O_3 particles with a density of 3.95 g/cm^3 and a particle size of 3μ÷6μm. Particle bindings were formed basing on the technology described in [5, 9] based on the use of hydrated glass water solution $Na_2O \cdot nSiO_2 \cdot xH_2O$ (n, x - stoichiometric coefficients) hardened with CO_2.

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.

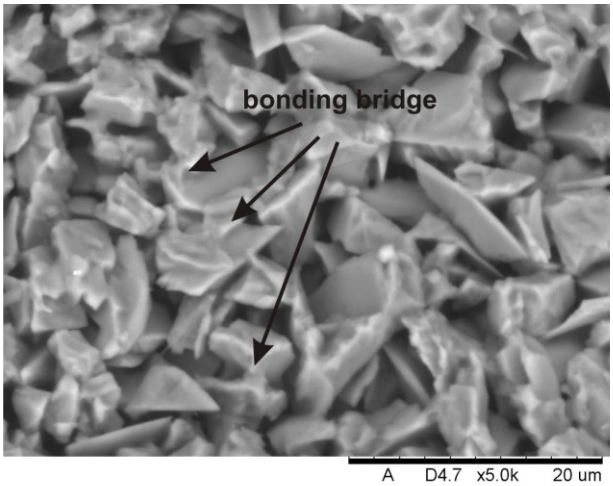

Fig. 1. Preform structure made of Al_2O_3 particles

Table 1.
Summary results EDS

Element	Mass %	Atomic %
Aluminum	43.831	35.918
Oxygen	31.650	43.740
Sodium	5.951	5.724
Silicon	18.568	14.618

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/cm^3), 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.

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

Weight fraction [%]	Si	Fe	Cu	Mn	Zn	Ti
Matrix AC-44200	10,5-13,0	0,55	0,05	0,35	0,10	0,15
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. Al_2O_3 particles is shown in Figure 2.

Composite samples taken from castings containing respectively 10, 20, 30 and 40% vol. of Al_2O_3 reinforcing particles were tested. For comparative purposes, the research was also carried out on the EN AC-44200 materials unreinforced with particles.

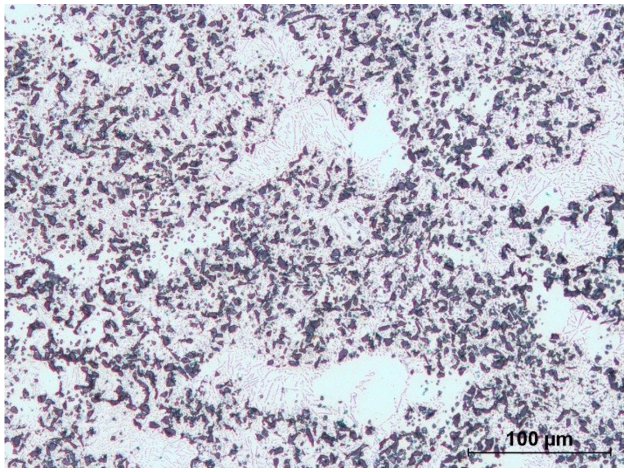

Fig. 2. Microstructure of a composite material EN AC-44200-20% vol. Al_2O_3 particles

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 l_o = 30.0 mm were used. The tensile test was performed at 23ºC and at 300ºC.

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.

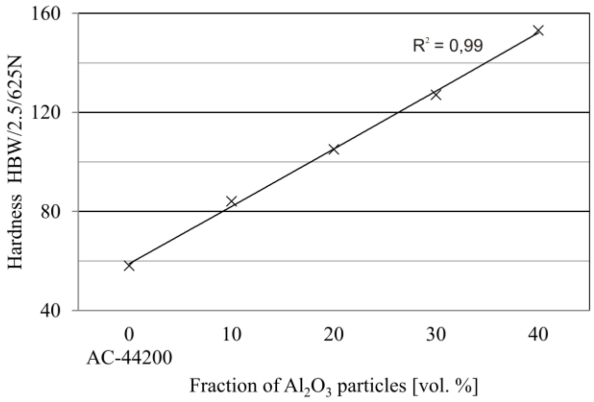

Fig. 3. Brinell hardness HBW/2.5/625N EN AC-44200 - Al_2O_3 particles

Strengthening of EN AC-44200 matrix with 10 vol.% of Al_2O_3 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.

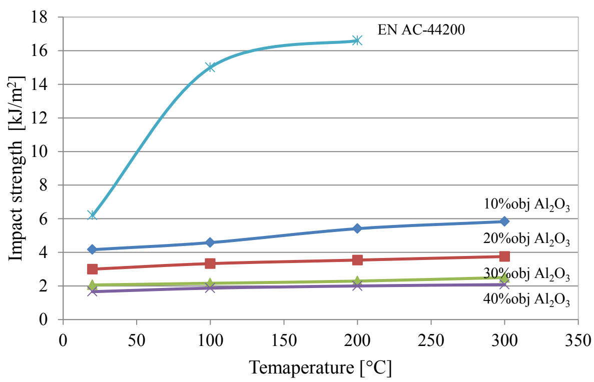

Fig. 4. Impact strength of composite materials AC44200-Al_2O_3

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/m^2] 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/m^2. 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 Al_2O_3 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% Al_2O_3 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 Al_2O_3 particles keeping a constant value of the impact strength of approximately 2 kJ/m^2 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 3.
Tensile strength

	R_m [MPa]			
Temperature	23°C		300°C	
Material	min	max	min	max
AC44200	150	163	-	-
AC44200+10%Al_2O_3	245	258	135	142
AC44200+20%Al_2O_3	240	253	147	158
AC44200+30%Al_2O_3	227	236	143	150
AC44200+40%Al_2O_3	198	210	124	137

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 $R_{p0,2}$ 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 Al_2O_3 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 R_m 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 R_m. At 300°C, the highest strength R_m values showed samples with 20% vol. of Al_2O_3 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.

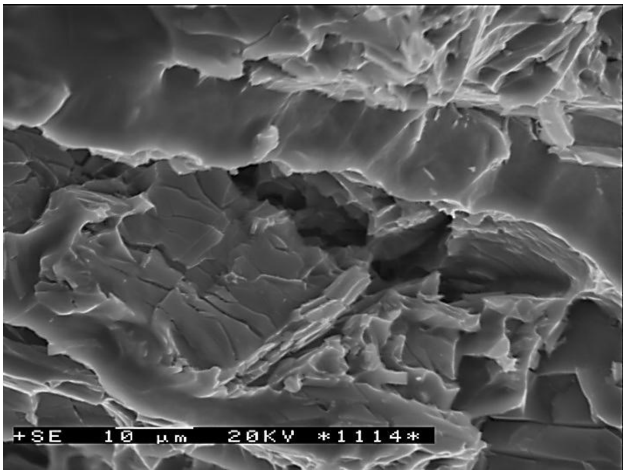

Fig. 5. Fracture of unreinforced EN AC-44200 after an impact test at 23°C

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 Al_2O_3 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).

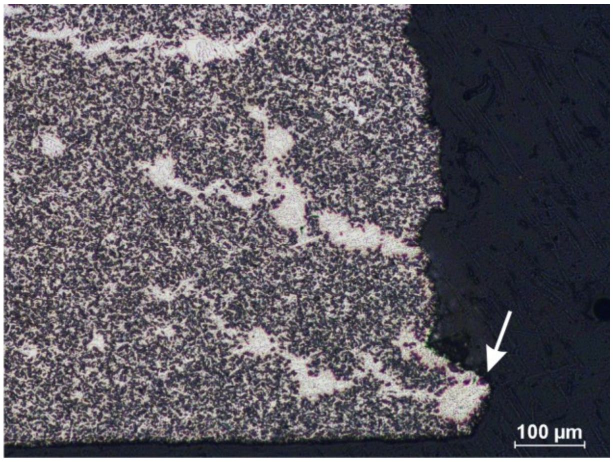

Fig. 6. Microstructure of EN AC-44200-30% vol. of Al_2O_3 after the impact test - edge and cracks area. T: 23°C

In the samples observed from a hammer impact side, many additional brittle cracks can also be observed, leading to composites' fragmentation (Figure 7). Propagation of additional cracks goes mainly in a perpendicular direction to the direction of hammer's impact and at 23°C passes through both the matrix material and a particle / matrix interfaces (Figure 8).

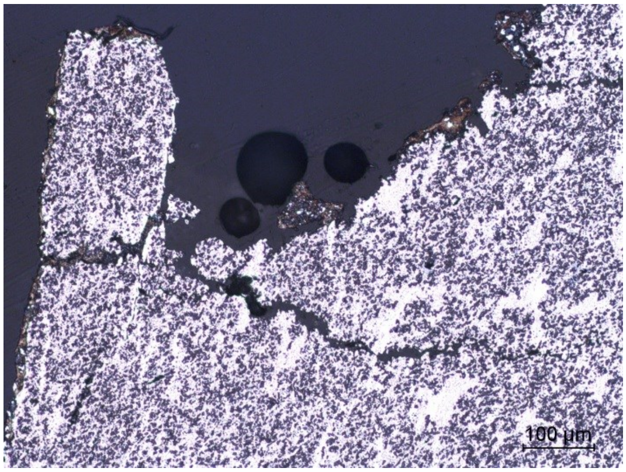

Fig. 7. Microstructure of EN AC-44200-20% vol. of Al_2O_3 after the impact test - edge and cracks area. T: 23°C

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 Al_2O_3 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.

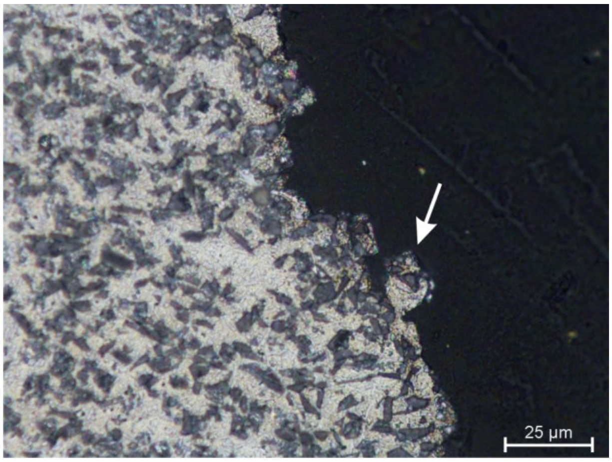

Fig. 8. Microstructure of composite material EN AC-44200-10% vol. of Al_2O_3 particles. Temp.: 23°C

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).

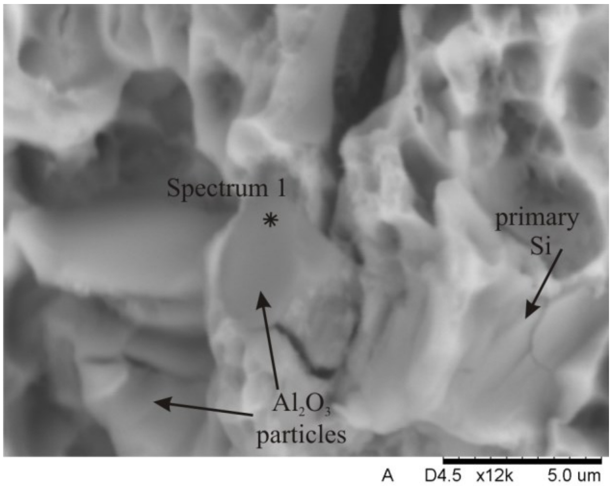

Fig 9. SEM of crack surface of material EN AC-44200-20% vol. Al_2O_3. Temp.: 23°C

Table 4.
Spectrum 1 - summary results EDS

Element	Mass %	Atomic %
Al K	46.39	33,90
O K	53.61	66.10
Totals	100.00	100.0

At the higher temperatures, and in particular at 300°C, Al_2O_3 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).

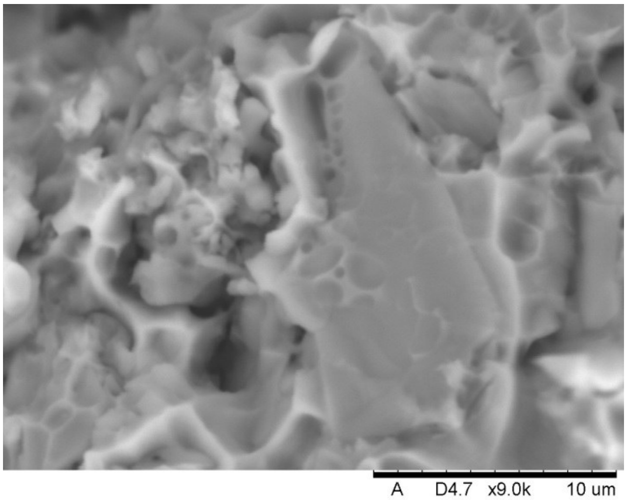

Fig. 10. SEM of the crack surface of material EN AC-44200-20% vol. of Al_2O_3. T: 300°C

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 Al_2O_3 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/m^2 comparing with the 2.0 kJ/m^2 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 Al_2O_3 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 Al_2O_3 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

[1] Shalaby, E.A.M., Churyumov, A.Y., Solonin, A.N. & Lotfy, A. (2016). Preparation and characterization of hybrid A359/(SiC+Si_3N_4) composites synthesized by stir/squeeze casting techniques. *Materials Science & Engineering*. A 674, 18-24.

[2] Jiang, J. & Wang, Y. (2015). Microstructure and mechanical properties of the rheoformed cylindrical part of 7075 aluminum matrix composite reinforced with nano-sized SiC particles. *Materials and Design*. 79, 32-41.

[3] Chou, S-N., Huang, J-L., Lii, D-F. & Lu, H-H. (2007). The mechanical properties and microstructure of Al_2O_3/aluminum alloy composites fabricated by squeeze casting. *Journal of Alloys and Compounds*. 436, 124-130.

[4] Konopka, Z., Łągiewka, M., Zyska, A. & Nadolski, M. (2009). Structural stability at elevated temperatures of the AlSi6Cu4 matrix composite with graphite particles. *Archives of Foundry Engineering*. 13(2), 57-60.

[5] Kaczmar, J.W., Granat, K., Kurzawa, A. & Grodzka, E. (2014). Physical Properties of Copper Based MMC Strengthened with Alumina. *Archives of Foundry Engineering*. 14(2), 85-90

[6] Shirvanimoghaddam, K., Khayyam, H., Abdizadeh, H., Akbari, M.K., Pakseresht, A.H., Abdi, F. Abbasi, A. & Naebe, M. (2016). Effect of B_4C, TiB_2 and $ZrSiO_4$ ceramic particles on mechanical properties of aluminium matrix composites: Experimental investigation and predictive modeling. *Ceramics International*. 42, 6206-6220.

[7] Ni, D.R., Chen, D.L. Wang, D., Xiao, B.L. & Ma, Z.Y. (2014). Tensile properties and strain-hardening behaviour of friction stir welded SiCp/AA2009 composite joints. *Materials Science & Engineering*. A(608), 1-10.

[8] Tang, S.W., Liu, C., Yu, Y.C., Hu, J. & Kong, L.C. (2015). The microstructure and tensile properties of Al_2O_3-coated $Al_{18}B_4O_{33}$ whisker reinforced AA2024 aluminum composite. *Materials Chemistry and Physics*. 149-150, 282-287.

[9] Kaczmar, J.W. & Kurzawa, A. (2012). The effect of α-alumina particles on the properties of EN AC-44200 Al alloy based composite materials. *Journal of Achievements in Materials and Manufacturing Engineering*. 55/1, 39-44.

[10] Rui-Fen, G., Ping, S., Shi-Xin, L, Alateng, S. & Qi-Chuan, J. (2017). High compressive strength in nacre-inspired Al−7Si−5Cu/Al_2O_3–ZrO_2 composites at room and elevated temperatures by regulating interfacial reaction. *Ceramics International*. 43, 7369-7373.

[11] Shin, S.E., Ko, Y.J. & Bae, D.H. (2016). Mechanical and thermal properties of nanocarbon-reinforced aluminum matrix composites at elevated temperatures. *Composites*. B 106, 66-73.

[12] Kurzawa, A. & Kaczmar, J.W. (2017). Bending Strength of EN AC-44200 – Al_2O_3 Composites at Elevated Temperatures. *Archives of Foundry Engineering*. 17(1), 103-108.

[13] Uematsu, Y., Tokaji, K. & Kawamura, M. (2008). Fatigue behaviour of SiC-particulate-reinforced aluminium alloy composites with different particle sizes at elevated temperatures. *Composites Science and Technology*. 68, 2785-2791.

[14] Mohan, T. & Manoharan, N. (2015). Experimental investigation of tensile and impact behavior of aluminium metal matrix composite for turbocharger. *ARPN Journal of Engineering and Applied Sciences*. 10/13, 5672-5674

[15] Hindi, J., Achutha Kini, U.A., Sharma S.S., Gurumutry, B.M. & Gowri Shankar, M.C. (2015). Mechanical Characterization of Stir Cast Al 6063 Matrix SiC Reinforced Metal Matrix Composites. *Mechanical and Materials Engineering*.

[16] Ibrahim, M.F., Ammar, H.R., Samuel, A.M, Soliman, M.S. & Samuel, F.H. (2015). On the impact toughness of Al-15 vol.5 B_4C metal matrix composites. *Composites*. B 79, 83-94

[17] Bonello, F., Ceschini, L. & Garagnani, G.L. (1997). Mechanical and Impact Behaviour of $(A1_20_3)$p/2014 and (A1203)p/6061 A1 Metal Matrix Composites in the 25-200°C Range. *Applied Composite Materials*. 4, 173-185

[18] Ozden, S., Ekici, R. & Nair, F. (2006). Investigation of impact behaviour of aluminium based SiC particle reinforced metal–matrix composites. *Composites*. A (38), 484-494.