ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering
Tome VI (Year 2013) – FASCICULE 3 [July–September]
ISSN 2067–3809

[1.] K. K. ALANEME, [2.] M. O. BODUNRIN

MECHANICAL BEHAVIOUR OF ALUMINA REINFORCED AA 6063 METAL MATRIX COMPOSITES DEVELOPED BY TWO STEP – STIR CASTING PROCESS

[1-2.] DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING, FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE, NIGERIA

ABSTRACT: Among metallic matrices, Aluminum based matrix remains the most explored metal matrix material for the development of MMCs. This is primarily due to the broad spectrum of properties offered by aluminum based matrix composites at low processing cost. The mechanical behavior of aluminum alloy (6063) - alumina particulate composites developed using two step stir casting was investigated. AA 6063 - Al_2O_3 particulate composites having 6, 9, 15, and 18 volume percent of Al_2O_3 were produced. It is observed that AA 6063/Al_2O_{3p} composites having low porosity levels (≤ 3.51 %porosity) and a good uniform distribution of the alumina particulates in the matrix of the AA 6063 were produced. The tensile strength, yield strength, and hardness increased with increase in alumina volume percent while the strain to fracture and fracture toughness decreased with increasing volume percent alumina.
KEYWORDS: stir casting; AA6063-Al_2O_3, fracture toughness, tensile properties, porosity

INTRODUCTION

The viability of developing simple, cost effective and technically efficient processing routes for the production of metal matrix composites (MMCs) is currently being explored by materials researchers from most developing countries [1 - 2]. The motivation for research in MMCs development is its attractive properties and higher performance potentials over traditional metals and alloys [3 - 4]. Some of the desirable properties of MMCs include high specific strength and stiffness, better high temperature performance, and low thermal expansion [5-6]. Among metallic matrices, Aluminum based matrix remains the most explored metal matrix material for the development of MMCs. This is primarily due to the broad spectrum of properties offerred by aluminium based matrix composites at low processing cost [6]. Currently, Aluminum based matrix composites are applied in the design of a wide range of components for use in aerospace technology, defense, electronic heat sinks, solar panel substrates, antenna reflectors, automotive drive shaft fins, explosion engine components, and sports equipment among others [6 - 7].

Deriving optimized properties from any selected Al based matrix composite requires a sound knowledge of the material behavior of the composite which is influenced by such factors as the base Al alloy composition, the manufacturing process, the reactivity between the reinforcement and the matrix, the size, morphology and volume fraction of the reinforcement [8 - 10].

The current research work is an effort to study the mechanical behaviour of AA (6063)/ Al_2O_{3p} composites produced using two step stir casting process. AA 6063 is processed in large quantities at lower costs in many developing countries but its potentials for use as Al alloy matrix for composite development has not been explored as extensively as the other age hardenable Al alloy series such as the AA 6061, AA 7075, and AA 2024 series [8, 11 - 12].

MATERIALS AND METHODS. Materials

The materials utilized in the present study are 100 percent chemically pure alumina (Al_2O_3) particles having a particle size of 28 μm and Aluminum 6063 alloy which served as the matrix. The composition of the Aluminum 6063 alloy is shown in Table 1.

Table 1: Chemical Composition of the Aluminum Alloy 6063 (AA 6063)

Si	Fe	Cu	Mn	Mg
0.45	0.22	0.02	0.03	0.50

Zn	Cr	Ti	Al
0.02	0.03	0.02	Bal.

Methods

☐ ***Stir Casting***

The quantity of Aluminium (6063) alloy and alumina (Al_2O_3) particles required to produce composites having 6, 9, 15, and 18 volume percent alumina were evaluated using charge calculations. The alumina particles were initially preheated at a temperature of 250^{0}C for 5minutes to help improve wettability with the AA 6063 alloy. The AA 6063 ingots were charged into a gas-fired crucible furnace and heated to a temperature of 750^{0}C ± 30^{0}C (above the liquidus temperature of the alloy) and the liquid alloy was

then allowed to cool in the furnace to a semi solid state at a temperature of about 600^{0}C.
The preheated alumina was added at this temperature and stirring of the slurry was performed manually for 5 minutes. The composite slurry was then superheated to 720^{0}C and a second stirring performed using a mechanical stirrer. The stirring operation was performed at a speed of 300 rpm for 10 minutes to help improve the distribution of the alumina particles in the molten AA 6063.
An external temperature probe (thermocouple) was utilized to monitor the temperature of the furnace. The molten composite was then cast into prepared sand moulds. Unreinforced AA 6063 were also prepared by casting for control experimentation.

□ ***Hardness Measurement***

The hardness of the composites was evaluated using a Vickers Hardness Tester (LECO AT 700 Microhardness Tester). Prior to testing, the surface of the composite test specimens of sizes 25 × Ø20 mm were subjected to grinding and polishing operation to obtain a flat and smooth surface finish. A direct load of 50gf (490.3 mN) was then applied on the specimens for 10 seconds and the hardness readings evaluated following standard procedures.
Multiple hardness tests were performed on each sample and the average value taken as a measure of the hardness of the specimen.

□ ***Density Measurement***

The density measurements were carried out to determine the porosity levels of the samples. This was achieved by comparing the experimental and theoretical densities of each volume percent Al_2O_3 reinforced composite.
The experimental density of the samples was evaluated by weighing the test samples having dimensions of 20 mm diameter and 220 mm length using a high precision electronic weighing balance with a tolerance of 0.1mg. The measured weighs in each case was divided by the volume of the respective samples.
The theoretical density of composite was evaluated by using the rule of mixtures given by:

$$\rho_{AA\frac{6063}{Al_2O_{3p}}} = Vol._{AA6063} \times \rho_{AA6063} + Vol._{Al_2O_3} \times \rho_{Al_2O_3} \quad (2.1)$$

where, $\rho_{AA\frac{6063}{Al_2O_{3p}}}$ *= Density of Composite,*

$Vol._{AA6063}$ *= Volume fraction of AA 6063,*

ρ_{AA6063} *= Density of AA 6063,*

$Vol._{Al_2O_3}$ *= Volume fraction Al_2O_3, and*

$\rho_{Al_2O_3}$ *= Density of Al_2O_3.*

The percent porosity of the composites was evaluated using the relations [12]:

$$\% \text{ porosity} = \{(\rho_T - \rho_{EX}) \div \rho_T\} \times 100\% \quad (2.2)$$

where, ρ_T *=Theoretical Density (g/cm^3),*

ρ_{EX} *= Experimental Density (g/cm^3)*

□ ***Tensile Testing***

Room temperature uniaxial tension tests were performed on round tensile samples machined from the monolithic alloy and the composites with dimensions of 6 mm diameter and 30 mm gauge length.
The testing was performed using an instron universal testing machine operated at a constant cross head speed of 1mm/s; and the procedure adopted was in conformity with ASTM E8M - 91 standards [13]. Three repeat tests were performed for each test condition to guarantee reliability of the data generated.
The tensile properties evaluated from the stress-strain curves developed from the tension test are - the ultimate tensile strength (σ_u), the 0.2% offset yield strength (σ_y), and the strain to fracture (ε_f).

□ ***Fracture Toughness, K_{1C}***

Circumferential notch tensile (CNT) specimens were prepared for the evaluation of fracture toughness in accordance with Alaneme [14]. The CNT specimens were machined with gauge length of 30mm, specimen diameter of 6mm (D), notch diameter of 4.5mm (d) and notch angle of 60^0.
The specimens were then subjected to tensile loading to fracture using an instron universal testing machine. The fracture load (P_f) obtained from the CNT specimens' load - extension plots were used to evaluate the fracture toughness using the empirical relations by Dieter [15]:

$$K_{1C} = P_f / (D)^{3/2} [1.72(D/d) - 1.27] \quad (2.3)$$

Where, D and d are respectively the specimen diameter and the diameter of the notched section. The validity of the fracture toughness values was evaluated using the relations in accordance with Nath and Das [16]:

$$D \geq (K_{1C} / \sigma_y)^2 \quad (2.4)$$

A minimum of two repeat tests were performed for each treatment condition and the results obtained were taken to be highly consistent if the difference between measured values for a given treatment condition is not more than 2%.

□ ***Microstructure***

The microstructural investigation was performed using a Datteng Software-Driven Metallurgical Microscope. The specimens for the optical microscopy were polished using a series of emery papers of grit sizes ranging from 500µm - 1500µm; while fine polishing was performed using polycrystalline diamond suspension of particle sizes ranging from 10µm - 0.5µm with ethanol solvent. The specimens were etched using 1HNO_3: 1HCl solution by swabbing in accordance with Yussof et al [17] before microstructural examination was performed using the optical microscope.

RESULTS AND DISCUSSION. Microstructure

Figure 1 shows representative optical micrograph for the 9 and15 volume percent Al_2O_3 reinforced AA 6063 composites. It is observed that the Al_2O_3 particulates are visible and a good dispersion of the particulates in the AA 6063 matrix is evident. This is a good indicator of the efficiency of the production technique.

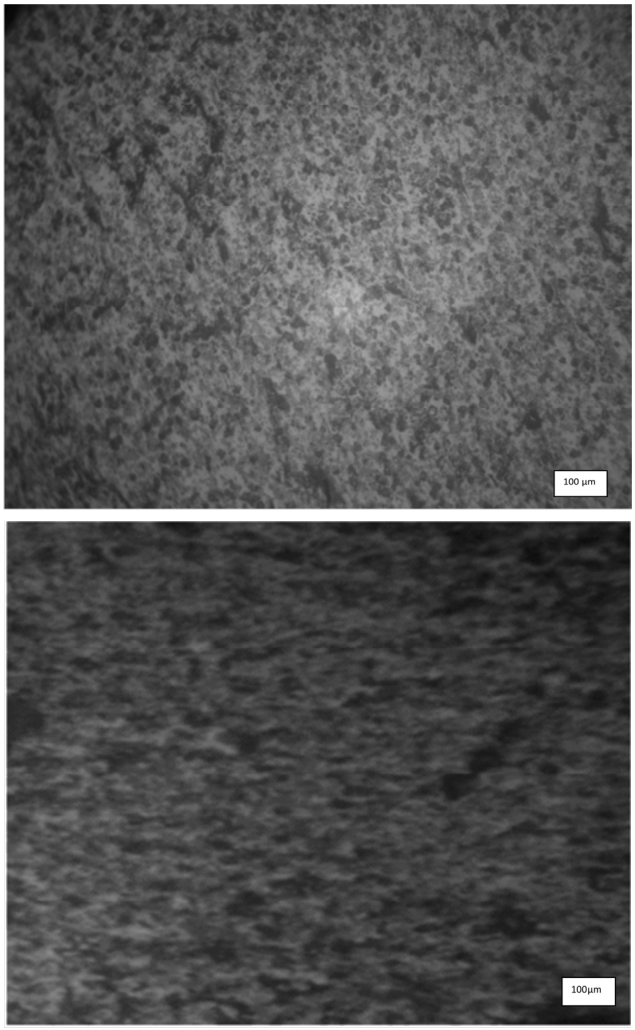

Figure 1: Representative Micrographs for (a) AA 6063 - 9 vol% Al_2O_3, and (b) AA 6063 - 15 vol% Al_2O_3

Percent Porosity

The results of the percent porosity of the composites are presented in Table 2. It is observed that slight porosities exist in the produced composites since the experimental densities are lower than the theoretical densities. It is however encouraging that the percent porosities are between 1.08 - 3.51% which is within the acceptable range of 4% porosity reported in literature as the maximum permissible in cast metal matrix composites [18-19].

Table 2: Percent Porosity and Hardness data for the AA 6063 – Al_2O_3 Composites

Materials Samples	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	% Porosity	Hardness (VHN)
0%	2.70	2.68	0.74	40.3 ± 0.2
6%	2.76	2.69	2.54	40.5 ± 0.1
9%	2.79	2.74	1.79	41.4 ± 0.4
15%	2.85	2.75	3.51	43.6 ± 0.2
18%	2.87	2.77	3.48	45.1 ± 0.3

The low porosity levels are attributed to the two - step stirring process adopted for producing the composites. The manual mixing operation performed in the semi-solid state helps to break the surface gas layers and to spread the liquid metal onto the surface of the particles. It also reduces the surface tension between the AA 6063 melt and the particles to facilitate easier wetting and mixing of the alumina particulates in the melt.

The mechanical stirring employed at the liquidus state helps in reducing the sedimentation of alumina particles by virtue of their higher density ($3.95g/cm^3$); and also improve the dispersion of the alumina particulates.

Mechanical Properties

The variation of hardness with volume percent Al_2O_3 is also presented in Table 2. It is observed that the hardness increases with increase in volume percent Al_2O_3. This trend is due to an increase in the proportion of the hard Al_2O_3 particulates in the composites, which increases the composites resistance to indentation in comparison to the monolithic alloy [18].

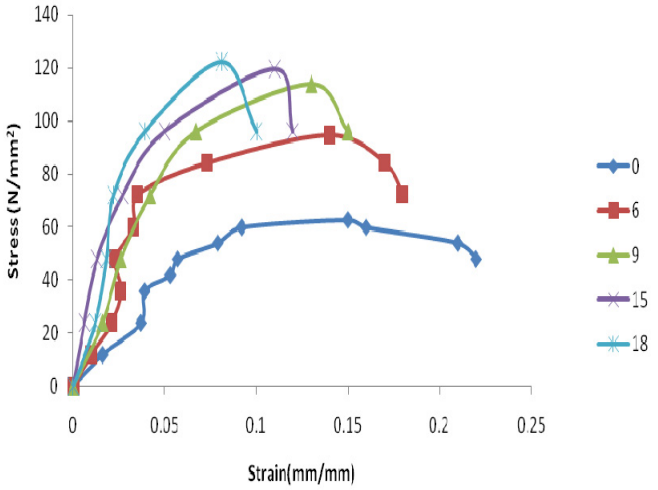

Figure 2: Tensile Stress - Strain curves of the AA 6063 - Al_2O_3 Composites.

The stress-strain plots of the composites are presented in Figure 2; while the variation of ultimate tensile and yield strengths and strain to fracture are presented in Figures 3 - 4. It is observed from the stress - strain plots that the monolithic alloy has the largest plastic strain and also exhibits the least resistance to plastic deformation judging from its relatively lower flow stress in comparison with the composites.

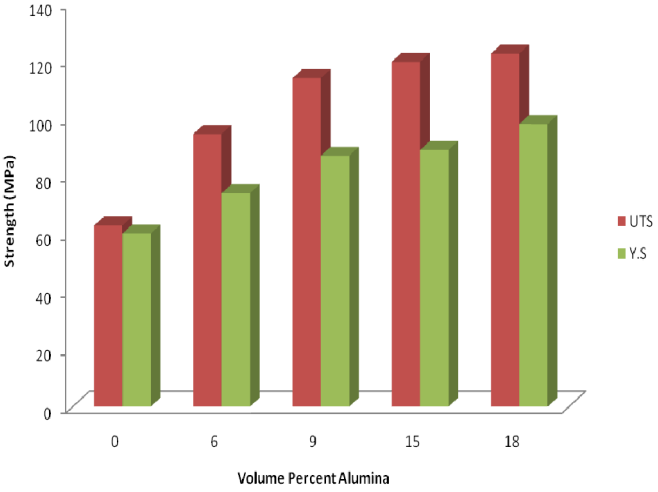

Figure 3- Variation of Ultimate Tensile and Yield Strengths in the Composite with increase in Volume percent alumina reinforcement.

Figure 3 shows clearly that the ultimate tensile and yield strengths of the composites increases with increase in volume percent alumina.

The observed trend is in conformity with observations in most hard particulate reinforced metal matrix composites [20-21]. The strengthening mechanisms has been well reported by Chawla and Shen [22] who attributed it to increased load sustaining capacity of the composite with increase in the volume percent of the hard particulates; and the increased resistance to dislocation movement by the particulates.
The resulting thermal mismatch between the high expansion metallic matrix and the low expansion ceramic particulates results in the generation of dislocations at the reinforcement/matrix interface upon cooling, contributing to an increase in dislocation density in the composites with increasing particulate content [22 - 23].

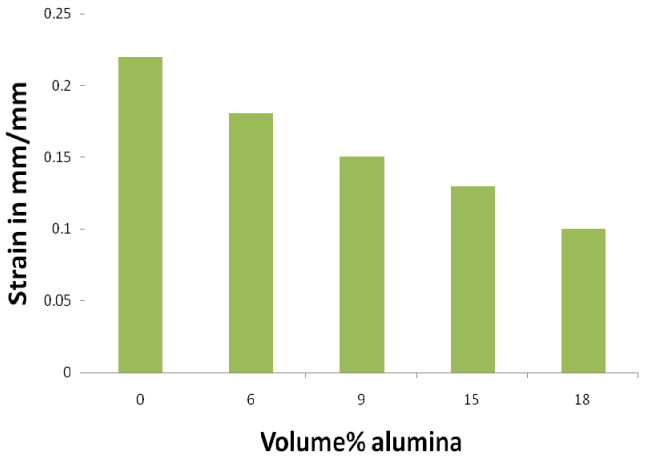

Figure 4: Variation of Strain to fracture with increase in volume percent alumina particulates

The strains to fracture for the composites (Figure 4) are observed to decrease with increase in volume percent alumina; and the values are observed to be less than 0.19 (19%). The increased matrix/ particulate interfaces with increase in volume percent alumina leads to an increase in the potential sites for void nucleation or micro-crack formation. The uneven plastic strain at the interface facilitates the nucleation of voids or micro-cracks [22-24].

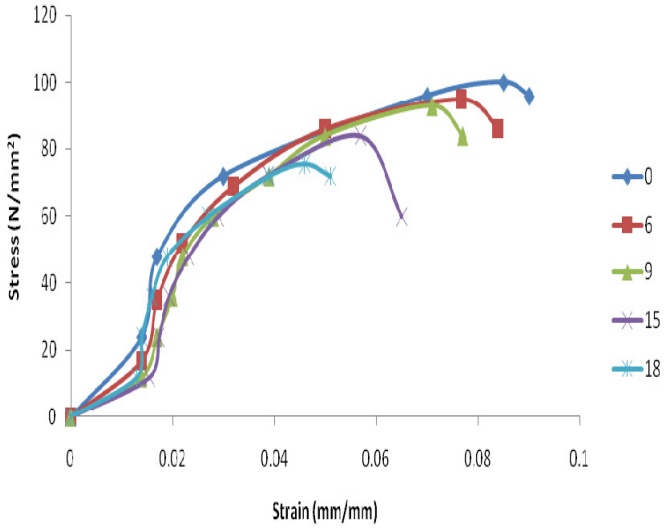

Figure 5: Stress - Strain curves for the CNT tests on the AA 6063 - Al_2O_3 Composites

The fracture loads utilized for the evaluation of the fracture toughness were derived from the stress - strain plots of the circumferential notch tensile specimens (Figure 5).

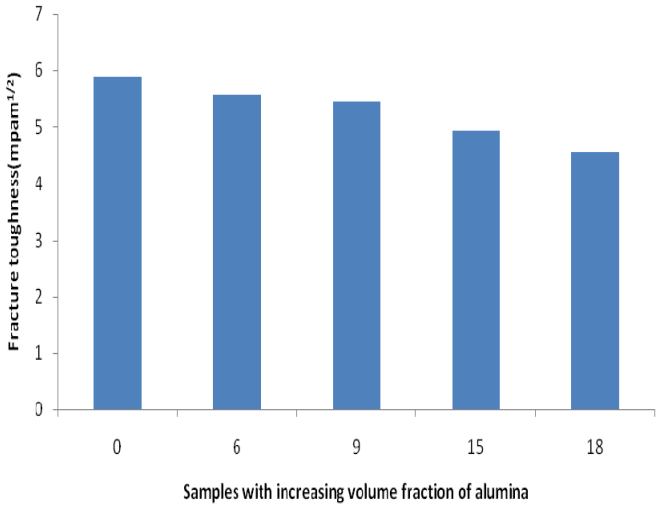

Figure 6: Variation of Fracture Toughness with increase in volume percent of alumina particulates

The variation of fracture toughness of the composites with increase in Al_2O_3 volume percent is presented in Figure 6. The results were taken to be reliable because the requirement for nominal plain strain condition was met with the specimen diameter of 6mm since the relation $D \geq (K_{1C}/\sigma_y)^2$ [16] was utilized to test for the validity of the K_{1C} values evaluated from the CNT testing.
The fracture toughness (which is a measure of the composites resistance to crack propagation) was observed to decrease with increase in volume percent of Al_2O_3 which is consistent with the trend in most hard particle reinforced metal matrix composites [22, 25-26].
The increased sites (particles, particle/matrix interfaces, and particle clusters) for crack nucleation with increasing volume percent of the Al_2O_3 were responsible for the observed trend [26 - 27]. The fracture micro-mechanism may be due to particulate cracking, interfacial cracking or particle debonding [27 - 28]. Generally, the fracture toughness values obtained for the composites were found to be comparable to that of Al matrix composites processed under similar conditions [29-30].

CONCLUSIONS

From the results of this research investigation, It has been established that low porosity levels less than 3.6% is observed in AA 6063/Al_2O_{3p} composites developed by the two step stir casting process adopted in this research.
The tensile strength, yield strength, and hardness values of the composites increased with increase in alumina volume percent while the strain to fracture and fracture toughness decreased with increasing volume percent alumina.
The mechanical properties obtained from the AA 6063/Al_2O_{3p} composites developed compares favorably with that of other aluminum based alumina reinforced composites reported in literature.

REFERENCES

[1.] Soboyejo W. Mechanical Properties of Engineered Materials. New York: Marcel Dekker Inc., 2003.

[2.] Miracle, DB. Metal Matrix Composites-From Science to technological significance. Composites Sci and Tech 2005; 65(15-16): 2526-2540.

[3.] Anilkumar H. C., Hebbar H. S. and Ravishankar K. S. Mechanical Properties of Fly Ash Reinforced Aluminium Alloy (Al 6061) Composites. International Journal of mechanical and Materials Engineering 2011; 6 (1):41-45

[4.] Adiamak, M. Selected Properties of Aluminium Base Composites reinforced with intermetallic Particles, Journal of Achievemnets in Materials and Manufacturing Technology, 2006, 14 (1-2): 43-47.

[5.] Alaneme, K. K. Influence of Thermo-mechanical Treatment on the Tensile Behaviour and CNT evaluated Fracture Toughness of Borax premixed silicon carbide reinforced Aluminium (6063) Matrix Composites, International Journal of Materials and Mechanical Engineering, 2012, 7(1): 96 - 100.

[6.] Veeresh Kumar GB, Rao, CSP, Selvaraj N, Bhagyashekar MS. Studies on Al (6061) and 7075 - Al203 Metal Matrix Composites. J of Minerals & Matls Charac & Eng 2010; 9(1): 43-55.

[7.] Natarajan, N., Vijayarangan, S. and Rajendran, I. Fabrication, testing and thermal analysis of metal matrix composite brake drum. International Journal of Vehicle Design 2007, 443(4): 339-359.

[8.] Chawla V, Manoj S, Dwivedi D D, Lakhvit S. Development of Aluminium Based SiC Particulate Metal Matrix Composite 2009; J of Minerals & Matls Charac & Eng 2009; 8(6): 455-467.

[9.] Zamri, Y.B., Shamsul, J.B. and Amin, M.M. Potential of palm oil clinker as reinforcement in aluminium matrix composites for tribological applications, International Journal of Mechanical and Materials Engineering 2011; 6 (1): 10-17.

[10.] Cocen U, Onel K. Ductility and Strength of extruded SiCp/ aluminium alloy composites. Comp Sci and Tech 2002; 62: 275-282.

[11.] Christy T V, Murugan N, Kumar S. A Comparative study on the microstructures and Mechanical Properties of Al 6061 alloy and the MMC Al 6061/TiB2/12p. J Minrls and Matls Charac & Eng 2010; 9(1): 57-65.

[12.] Alaneme, K. K. and Aluko, A. O. Production and Age - hardening Behaviour of Borax Pre-mixed SiC Reinforced Al-Mg-Si alloy Composites developed by Double Stir Casting Technique, The West Indian Journal of Engineering, 2012, 34(1/2): 80 - 85.

[13.] ASTM E 8M . Standard Test Method for Tension Testing of Metallic Materials (Metric) in Annual Book of ASTM Standards. Philadelphia: ASTM; 1991.

[14.] Alaneme, K. K. Fracture Toughness (K_{1C}) Evaluation for Dual Phase low alloy Steels Using Circumferential Notched Tensile (CNT) Specimens, Materials Research, 2011, Vol. 14, No. 2, doi: 10.1590/S1516- 14392011005000028

[15.] Dieter G E. Mechanical Metallurgy, SI Metric Ed. Singapore: McGraw- Hill; 1988.

[16.] Nath S K, Das U K. Effect of Microstructure and Notches on the Fracture Toughness of Medium Carbon Steel. J Naval Archi & Marine Eng 2006; 3: 15 - 22.

[17.] Yussof Z, Ahmad K.R and S.B., Jamaludin Comparative Study of Corrosion Behavior of AA 2014/15vol%Al_2O_{3p} and AA2009/20Vol% SiCw, Portugaliae Electrochemica Acta, Volume 26, 2008, Pp 291-301.

[18.] Kok M. Production and Mechanical Properties of Al_2O_3 particle Reinforced 2024 Aluminium Composites, Journal of Materials Processing Technology. Volume 16, 2005, Pp. 381-387.

[19.] Hizombor M, Mirbagher S.M.H and Abdideh, Casting of A356/ TiB_2p Composite Based on the TiB_2p/ CMC / PPS MORTAR., Volume 18, 2010, Roznov pod Radhostem, Czech Republic, EU.

[20.] Dobrzanski L.A, Kremzer M., Nagel A. Aluminium EN Al-SiC Alloy Matrix Composite Reinforced by Al_2O_3 Preform, Achieves of Materials Science and Engineering, Volume 28, Issue 10, 2007, Pp 593-596.

[21.] Kumar S. and Theatan J.A., Production and Characterization of Aluminium Fly Ash Composites using stir Casting Method, B. Tech Thesis, National Institute of Technology, Pourkela. 2008.

[22.] Chawla N, Shen Y. Mechanical Behavior of Particle Reinforced Metal Matrix Composites. Advanced Engineering Materials 2001; 3(6): 357 - 370.

[23.] Ehsani R, Seyed Reihani S M. Aging Behaviour and Tensile Properties of Squeeze Cast Al 6061/ SiC Metal Matrix Composites. Scientia Iranica 2004; 11(4): 392-397.

[24.] Sharma S C, Girish B M, Kamath R, Satish B M. Fractography, Fluidity and Tensile Properties of Aluminium/Hematite Particulate Composites. J Matls Eng & Perf 1999; 8(3) 310 - 314.

[25.] Garcia-Romero A M, Egizabal P, Irisarri A M., Fracture and Fatigue Behaviour of Aluminium Matrix Composite Automotive Piston. Appl Compos Mater 2010; 17:15-30.

[26.] Perez.Ipina J E, Yawny A A, Stuke R, Gonzalez Oliver C. Fracture Toughness in Metal Matrix Composites. Materials Research 2000; 3(3): 74 - 78.

[27.] Mohammed M. Ranjbaran, Low Fracture Toughness in Al 7191-20%SiCp Aluminium Matrix Composite. European Journal of Scientific Research, Vol. 41, No. 2, 2010, Pp. 261-272.

[28.] Mortensen, A. A Review of the Fracture Toughness of Particle Reinforced Aluminium Alloys. Proc Int Conf Fabrication of Particulates Reinforced Metal Composites, Quebec, Canada 1999; 217 - 233.

[29.] Milan M T, Bowen P. Tensile and Fracture Toughness Properties of SiCp reinforced al alloys: Effects of Particle Size, Particle volume fraction and matrix strength, Journal of Materials Engineering and Performance 2004; 13(6) 775 - 783.

[30.] Alaneme, K. K. and Aluko, A. O. Fracture Toughness (K_{1C}) and Tensile Properties of As-Cast and Age-Hardened Aluminium (6063) - Silicon Carbide Particulate Composites, Scientia Iranica, Transactions A: Civil Engineering (Elsevier), 19(4), pp. 992 - 996.

ACTA TECHNICA CORVINIENSIS - Bulletin of Engineering

ISSN: 2067-3809 [CD-Rom, online]