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Empirical Models for Mechanical and Electrical Characteristics of Wrought Aluminium Alloy Reinforced with Silicon Carbide Particles

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Abstract. Aluminium matrix composites (AMCs) are advanced engineering materials used for a wide range of applications. AMCs consist of a non-metallic reinforcement incorporated into Aluminium matrix providing advantageous properties over base metal alloys. Wrought aluminium was reinforced with particulate silicon carbide of four different sizes and compositions using stir casting method. The resultant composites were subjected to mechanical and electrical tests. In this paper, empirical models were developed from measured laboratory data of micro-hardness, modulus, and electrical conductivity. Information obtained from the empirical models could be used as guidelines during the conceptual design and optimisation of manufacturing processes and thus, reducing time and costs.

Keywords: aluminium, silicon carbide, stir casting, mechanical properties, electrical properties, empirical models

1. Introduction

Metal Matrix Composite (MMC) is a material consisting of a metallic matrix combined with a ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) dispersed phase. Major MMCs are Aluminium Matrix Composites (AMC), Magnesium Matrix Composites, Titanium Matrix Composites and Copper Matrix Composites. However, the widest group of MMC is Aluminium Matrix Composites. Discontinuously reinforced aluminium matrix composites are fast emerging as engineering materials and competing with common metals and alloys. These are gaining significant acceptance because of higher specific strength, specific modulus and good wear resistance compared with unreinforced alloys [1]. AMCs are used in myriad of ways and according to Beffort [2], MMCs of the type 6061/B/50f, and A359/SiC/20p are used as cargo bay struts in space shuttle and brake disks and drums respectively. 2014/Al2O3/10-20p (Al-4.4Cu-0.5Mg-Si-Mn), 6061/ Al2O3/10-20p (Al-1.0Mg-0.6Si-Cu-Cr) and 7005/Al2O3/10p (Al-4.6Zn-1.4Mg-Mn-Cr-Zr-Ti) are used in bicycle frames, drive shafts and cylinder liner. A357/SiC/10-20p (Al-7.0Si-0.5Mg), A359/SiC/10-20p (Al-9.0Si-0.5Mg), A339/SiC/10-20p (Al-12Si-1.0Mg-1.0Ni-2.25Cu), A360/SiC/10-20p (Al-9.5Si-0.5Mg) and A380/SiC/10-20p (Al-8.5Si-3.5Mg) are applicable in brake drums and brake discs. 6061/Al2O3/10p is used in automobile drive shaft. 6092/SiC/17.5p and 2009/SiC/15p-T4 are used in fan exit guide vanes of jet engines. Al/Nextel610/45f is used for electrical conductors.

Production of MMC involves the use of one or more forms of energy. Electrical energy may be obtained from hydropower, nuclear energy, fossil fuel or renewable energy sources. Thermal and other



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mechanical energy in the manufacturing processes required energy that may also impact on the environment. For example, the furnace used in this work is fired by diesel oil. Other researchers in similar field used gas fired or electric furnaces. In all, there is always carbon imprint directly or indirectly. Furthermore, characterization of the composite; tensile, hardness, impact, fatigue, compression, microstructure tests et cetera also involve energy, time and money. Some or all these resources must be mitigated for sustainable production processes. Proven empirical equations are useful here.

Mathematical modeling of manufacturing process could be used to predict the product quality as well as the forces required. The information from modeling can be helpful in the design of product, tool, machine and process [3]. The mechanical and electrical properties could be modeled from measured properties and used to predict new composite design prior to actual processing and property measurement. For example, Lee and Pyo [4], used micromechanical framework to forecast the effective elastic property and weakened interface evolution of composites with embedded particles. The Eshelby's tensor for an ellipsoidal inclusion with slightly weakened interface was employed to model spherical particles having imperfect interfaces in the composites and is incorporated into the micromechanical framework. Vladimir and Oleksandr [5] worked on equation of state for aluminum silicon carbide using experimental p-V data. Jagadeesh et al. [6], constructed cooling curves for predicting temperature of Al 6061–SiCp composites. The theoretical predictions yielded a lot of information about the cooling rates of the cast composites with enormous time saving in experimentation. Suresha and Sridhara [7] on their part studied wear behaviour of stir cast Al–SiC–Gr hybrid composites considering the percentage of reinforcement (%), applied load (N), sliding distance (m), sliding speed (m/s) and subsequently generated a graphical model. Naher et al. [8], investigated the effect of viscosity during Al–SiC composite development. Focus were on production time (up to 65 min), mixing speeds (50–500 rpm), and particle sizes (13–100 µm) for two different viscosity levels (1 and 300 mPa s) were studied. Computer simulations, ambient temperature analogue fluid simulations, and MMC castings were performed. Volume fraction results of SiC at different locations within the fluids were assessed by each of these methods and compared. In the study, mechanical and electrical properties' models were developed from experimental data for product development by the industry's R and D department. Another investigator [12], used a different matrix (AA6061), different reinforcement (TiC) but the same stir casting method. He only produced model for Ultimate Tensile Strength whereas this present work has for Modulus, Hardness and Electrical Conductivity.

2. Methodology

In this work, stir casting method was used to prepare samples of AMCs using 1170Al reinforced with Silicon Carbide (SiC) particulates of 3 µm, 9 µm, 29 µm, and 45 µm sizes respectively. The chemical composition of Aluminium and Silicon Carbide are presented in Table 1 and Table 2 respectively.

Table 1 The Compositions in Percentage of Aluminium Ingot Obtained from Aluminium Rolling Mills, Ota

Fe	Si	Mn	Cu	Zn	Ti	Mg	Pb	Sn	Al
0.232	0.078	0.000	0.0006	0.0016	0.006	0.0027	0.0012	0.007	99.66

Table 2: The Chemical Composition in Percentage of Silicon Carbide (Logitech)

C	Al	Fe	Si	SiO ₂	Magnetic Iron	SiC
0.50	0.30	0.20	0.80	0.60	0.04	97.6

The liquid metallurgy route (stir casting technique) was adopted to prepare the cast composites. The advantages of stir casting method when compared with powder metallurgy and vacuum hot pressing include its simplicity, flexibility, economical, and suitability for mass production (industrial) and production of complex profiled composite components without damaging the reinforcement particles [9]. A batch of 5.0 kg of 1170Al was smelted in a graphite crucible using oil-fired tilting furnace at 750 °C [10]. A K-type thermocouple was used for melt temperature measurement. The molten metal was poured into a preheated mould (450 °C) and the melt agitated with a stirrer to form a fine vortex. The SiC particles were preheated (1100 °C) and added into the vortex with mechanical stirring at 500 rpm as in Abbassipour et al. [11] for about 5mins. Actual mixing occurs when the slurry is at semisolid form. The particle reinforced liquid alloy was allowed to cool. During solidification, the solid-liquid mixture is vigorously stirred to break up the dendritic structure. This procedure was repeated for reinforcement particle sizes of 3, 9, 29 and 45 µm at 2.5, 5.0, 7.5 and 10 wt. % of SiC respectively.

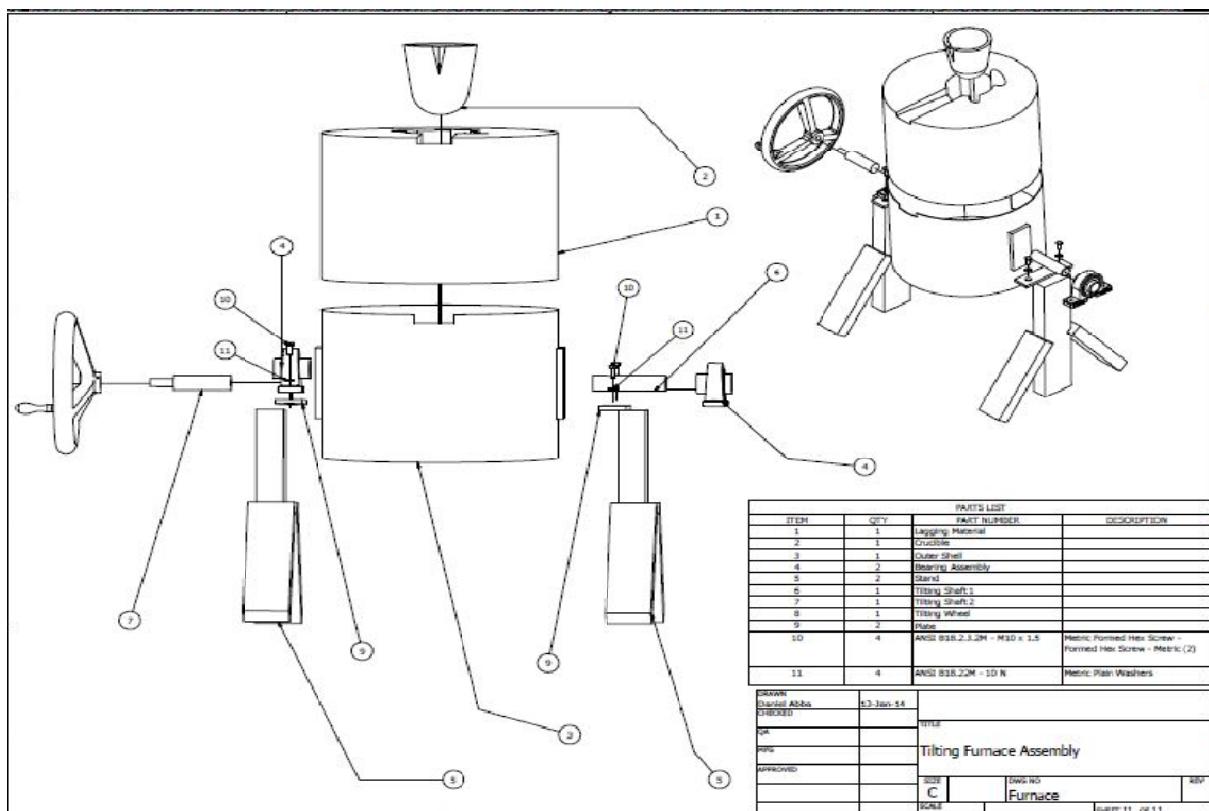


Fig. 1 Tilting Furnace Assembly Drawing [10]

Selected mechanical and electrical tests were conducted on the composites samples. The mechanical tests carried out were tensile and hardness, while the electrical tests were resistivity and conductivity for all the samples. Tensile specimens were machined to dimensions of 5 mm by 10 mm with a gauge length of 25 mm and pulled in Instron Universal Testing Machine (IUTM) with 30 KN load [13]. Micro hardness results were obtained using LECO 700AT tester with a load of 492.3mN and a dwell time of 10 seconds. Before testing, specimen surfaces were polished using emery papers down to 1000 mesh [14]. For electrical conductivity, samples with cross sectional dimensions of 5 mm by 10 mm and a length of 26 mm, were tested using 4-point probe set up machine [14]. The working voltage was 20 mV.

The results were processed using Excel, Design-Expert, and MATLAB software. From these, mathematical models were generated for simulation purposes. The proportion of the variance in the dependent variable that is predictable from the independent variable is the coefficient of determination, R². In this work, silicon carbide weight percent (w) and size (μ) were used to predict mechanical and electrical properties of AlSiC. A model equation with an R² closed to 1 is a good fit.

3. Result and Discussions

Summary of modeling equations obtained for modulus, hardness and electrical conductivity are presented in Tables 3 and 4. In Table 3, particle sizes and weight percentages were separately used to predict modulus, hardness and electrical conductivity. A known SiC weight percent/ particle size when fitted into the models, will predict modulus, hardness and electrical conductivity. The R² for these models were between 0.7143 to 0.9396 value.

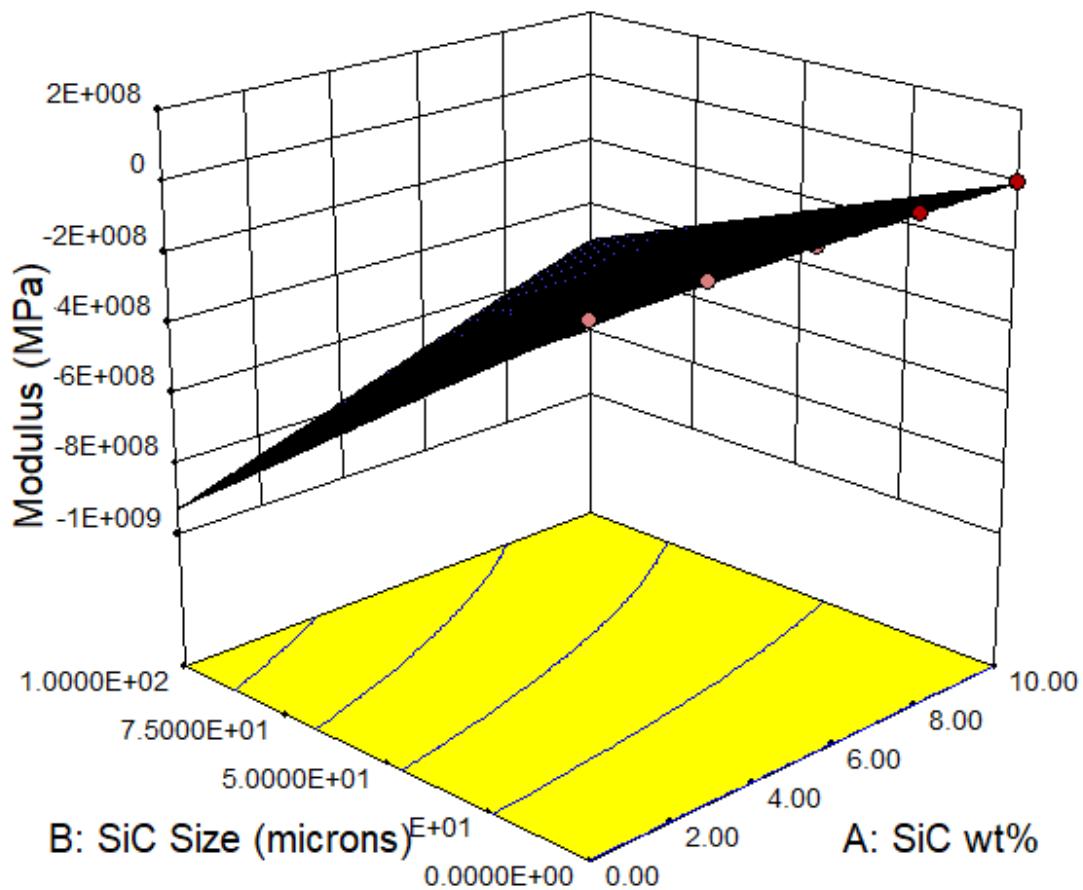
However, in Table 4, particle sizes and weight percentages were simultaneously used to predict modulus, hardness and electrical conductivity. The effect of particle sizes and weight percentages on modulus, hardness and electrical conductivity were shown graphically in Figures 2, 3 and 4 respectively. The models for predicting hardness and electrical conductivity have R² values of 0.8328 and 0.7513 respectively. The lowest value of R² was obtained for modulus at 0.4303

Table 3 Model Equations Using either Particle Sizes or Weight Percentages to Predict Composite Properties

S/N	AMC Designation	Fixed Parameter	Modulus (MPa)	Hardness (HV)	Electrical Conductivity (M Ω /m)
1	Al/SiC/2.5p/0 -45mm	Particle size	$\sigma = -1.6602m^2 + 70.061m + 736.63$	$H = 0.0843m + 20.64, R^2 = 0.7143$	$\sigma = 0.0013862m^2 - 0.093356m + 69.456$
2	Al/SiC/5.0p/0 -45mm	Particle size	$\sigma = -0.70001m^2 + 34.179m + 642.45$	$H = 0.239m + 21.19, R^2 = 0.8249$	$\sigma = 0.00058141m^2 - 0.15024m + 68.133$
3	Al/SiC/7.5p/0 -45mm	Particle size	$\sigma = -1.1501m^2 + 53.806m + 809.33$	$H = 0.2914m + 22.528, R^2 = 0.849$	$\sigma = 0.0073248m^2 - 0.37581m + 66.722$
4	Al/SiC/10p/0-45mm	Particle size	$\sigma = -0.84115m^2 + 39.97m + 545.32$	$H = 0.3135m + 22.838, R^2 = 0.8596$	$\sigma = 0.010671m^2 - 0.63267m + 59.546$
5	Al/SiCp/0-10/3mm	%wt.	$\sigma = -26.348w^2 + 310.57w + 459.39$	$H = 0.692w + 19.32, R^2 = 0.9396$	$\sigma = -1.908w + 73.473, R^2 = 0.7366$
6	Al/SiCp/0-10/9mm	%wt.	$\sigma = -20.971w^2 + 230.46w + 521.04$	$H = 0.652w + 20.63, R^2 = 0.8896$	$\sigma = -2.0238w + 72.088, R^2 = 0.9213$
7	Al/SiC/0-10/29mm	%wt.	$\sigma = -19.58w^2 + 246.53w + 86.04$	$H = 1.576w + 19.37, R^2 = 0.933$	$\sigma = -1.2244w + 71.671, R^2 = 0.8278$
8	Al/SiC/0-10/45mm	%wt.	$\sigma = -11.504w^2 + 148.65w + 359.56$	$H = 1.64w + 20.95, R^2 = 0.8637$	$\sigma = -1.7725w + 71.535, R^2 = 0.8204$

Table 4 Model Equations Using both Particle Sizes and Weight Percentages to Predict Composite Properties

S/N	AMC Designation	Modulus (MPa)	Hardness (HV)	Electrical Conductivity(M Ω /m)
1	Al/SiC/wp/mm	$\sigma = -3.581E+8 + (1.059E+8)m - (3.588E+8)w + (1.059E+8)m w - 505.994m^2$, R2 = 0.4303	H = 19.64284 + 0.56770m + 22369.27468m w, R2 = 0.8328	$\sigma_e = 73.41306 - 1.96183m + 23303.67772w$, R2 = 0.7513

Fig. 2 Effects of silicon carbide particle size (μm) and weight percentages on modulus (MPa) of the AlSiC Composite

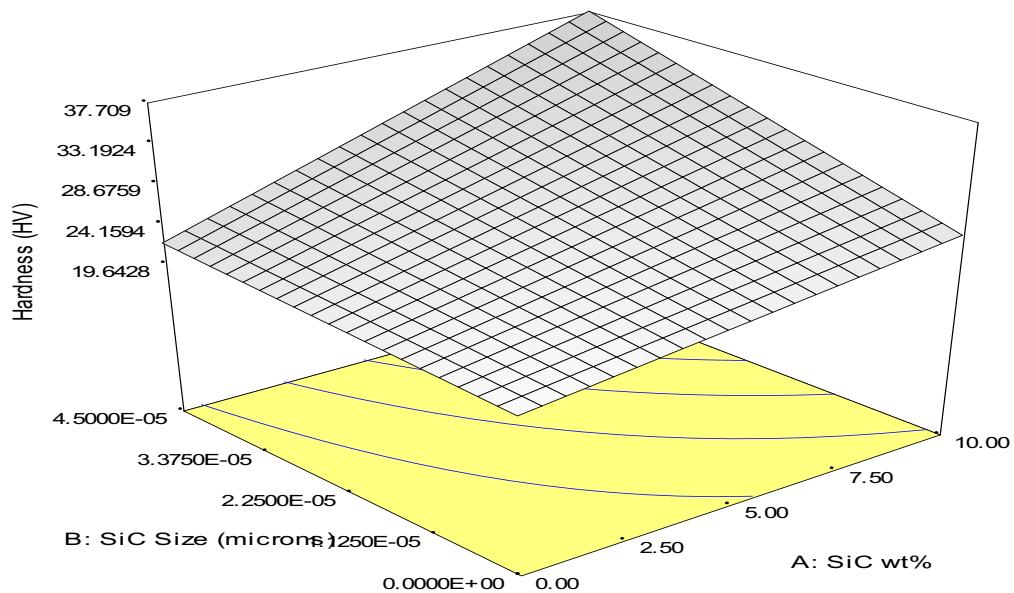


Fig. 3 Effects of silicon carbide particle size (μm) and weight percentages on hardness (HV) of the AlSiC Composite

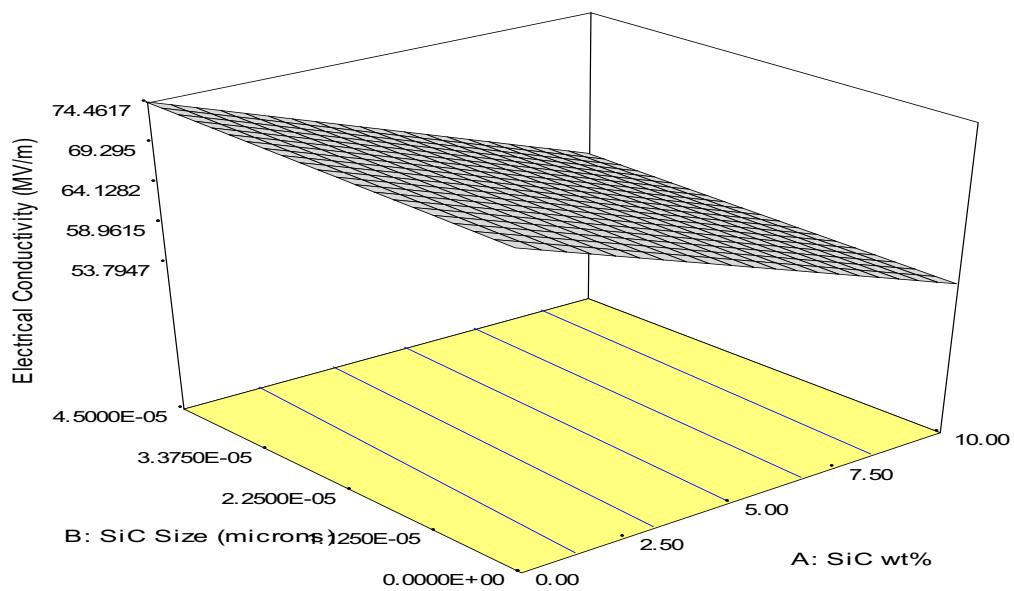


Fig. 4 Effects of silicon carbide particle size (μm) and weight percentages on electrical conductivity of the AlSiC Composite

4. Conclusions

Unlike the experimental approach which is time consuming, energy sapping with financial implications, the use of Excel, MATLAB and ANN method can generalize the complex relationships and provide approximate solutions. Mechanical properties are related to weight percentage and the size of SiC in the composite. Proven empirical equations obtained in this work are used to make informed decisions during the conceptual design and optimization of manufacturing processes. This makes the production process more sustainable by conserving energy, reducing time and reduction in financial resources.

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