



Thermo-Mechanical Analysis of Aluminium Silicon Carbide Composite Materials

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ABSTRACT: In recent years, composite materials have dominated the electronics industries and other manufacturing industries. Hence, composite materials like aluminium silicon carbide (AlSiC), has been employed to produce heat sinks, which are used mainly to manage heat in electronic devices. However, thermal fatigue of such composite material is a major challenge in maintaining reliability of the device. This paper investigates the thermo-mechanical effect of AlSiC composite materials. Finite element method (FEM) was used in the analyses of the composite materials based on the particulate inclusions between 10 – 50% compositions. The thermal profile (-40°C to 85°C) employed in this study is used commercially for consumer products. The fatigue life of the composite material which is based on the stresses and strains parameters were obtained and evaluated. The results from this investigation suggests that the deformations, strains, and stresses reduced with increase in the percentage of particulate inclusions. Also, the fatigue life of the composite material showed that the reliability of the material is increased with higher inclusions. This investigation demonstrated that 50% particulate inclusions has a better number of cycles to fatigue failure (5.09E+04) when compare to other inclusions. While 10% inclusions has the least fatigue life (4.39E+04) based on this investigation.

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In order to improve thermal management in electronic devices, the traditional materials initially used for managing heat has to be revolutionized. Copper and Aluminium are the most commonly used materials for heat management (Ekpu *et al* 2011). However, the use of composite materials have considerably enhanced heat management in electronic applications. Hence, the need to investigate the thermo-mechanical behaviours of composite materials are indeed necessary. Researchers such as (Babalola *et al* 2018; Xiao-min *et al* 2012; Wang *et al* 2009) have studied composite materials to determine their electrical, physical and mechanical properties. Babalola *et al* (2018), presented a study of the electrical and mechanical properties of AlSiC composite material produced by stir casting method. In their study, the experimental results gotten was infused into an Artificial Neural Network (ANN) to predict the properties of the composite material. The essence of the work was aimed at reducing the high cost of carrying out experiments and its related challenges. Kumar *et al* (2019), studied the integrity of the surfaces of aluminium based composite materials machined by Electrical Discharge Machine (EDM). Their study suggested that the surface defect of pure AlSiC composite materials were less than AlSiC composite materials that B₄C particles were added to. Hassan and Hussen (2017), investigated the

mechanical properties of AlSiC composite material. In their study, it was observed that the weight loss and wear rate of the AlSiC were lower than the pure aluminium after 5 minutes, for temperatures of 300°C and 400°C. Also, the Vickers micro-hardness of the AlSiC composites were higher than that of the aluminium.

Composite materials has been developed over the years by researchers with the help of numerical and finite element modelling techniques (Cao *et al* 2013; Wu and Yao 2010; Yvonnet *et al* 2008). This will help reduce several experimental works on composite materials development. Issues related to thermal reliability of composite materials can be found in literature (Heimann and Pohl 2014; Li *et al* 2014). Not much works are available in literature on thermal fatigue of composite materials used for thermal management in the electronic industries. Hence, it is imperative to study the thermal fatigue of AlSiC metal matrix composite material using finite element method. This research will give an insight on the reliability capabilities of different compositions of Aluminium Silicon Carbide composite materials.

MATERIALS AND METHODS

The model adopted in this research work, is centred on the simplicity of creating circular shaped particulates

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in virtual squared matrix domain. This was necessary for simulation purposes. Table 1 presents the geometric parameters used in developing the finite element design. The multiple inclusions for different composite models were created with ANSYS workbench simulation software. The design of the models were based on volume fraction, to ensure that a near practical solution is obtained. 1 μm to 200 μm

are the average sizes of particles obtained from most practical situations (Zhang *et al* 2007; Sahin and Acilar 2003; Sahin 2003). A two dimensional model was created for each of the multiple inclusions studied. It is assumed that the particles are uniformly distributed. The different composite models are presented in Fig. 1.

Table 1: Geometric Parameters

Inclusions (%)	Composite Domain for Multiple Inclusions (μm)	Diameter of Inclusions (μm)	Number of Multiple Inclusions
10	100 x 100	10	13
20	100 x 100	10	25
28	100 x 100	10	36
38	100 x 100	10	49
50	100 x 100	10	64

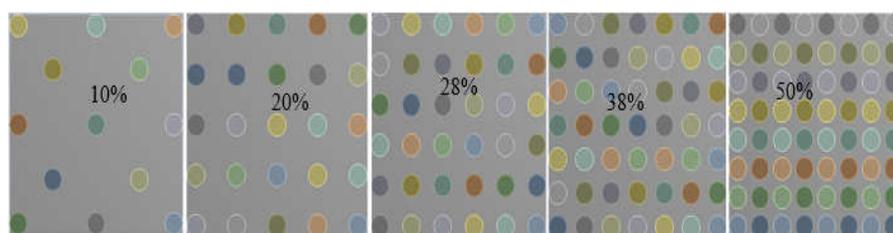


Fig. 1: Multiple Inclusions (10-50%) in a square matrix

Materials, Loads and Boundary Conditions: The material properties used in this research are recorded in (Steen and Ranzani 2000; Markolefas and Papanthassiou 2009). The material properties include: Young's Modulus of elasticity (E) of the matrix is 71 GPa and Poisson's ratio (ν) is 0.33 while for inclusions it is 410 GPa and 0.14 respectively. The multiple inclusions representative volume element (RVE) had the SiC inclusions uniformly distributed within the bulk of the matrix. This was to allow for computational simplicity. In practice, the particles in composite materials are randomly distributed. The study by (Zhang *et al* 2008) on interface failure, prompted the use of the volume fractions between 10-50% particulate inclusions. The square matrix is fixed around the edges of the models used in this research. While the JEDEC standard (JEDEC 2009) for commercial consumption category (-40 $^{\circ}\text{C}$ to 85 $^{\circ}\text{C}$) was used for the thermal cycling load profile. Several accelerated life testing (ALT) profiles has been used by researchers over the years (Cuddalorepatta and Dasgupta 2007; Anderson *et al* 2000; Cui 2005) to evaluate thermal effects on electronic devices. Read (Ekpu *et al* 2013; Ekpu *et al* 2014) for further information about the thermal cycle profile used in this research. According to (Boccaccini 1998), tensile thermal stresses (σ_{ts}) are induced when materials are subjected to thermal cycling. The thermal stress (σ_{ts}) is presented as:

$$\sigma_{ts} = \frac{CE\alpha\Delta T}{1 - \nu} \quad (1)$$

C is a non-dimensional constant, which is dependent on thermal cycling conditions characterized by the Biot modulus (β):

$$\beta = \frac{ah}{k} \quad (2)$$

$$\sigma_{ts,c} = \frac{CE_e\alpha_e\Delta T_c}{1 - \nu_e} \quad (3)$$

$$\Delta T_c = R = \frac{\sigma_t(1 - \nu)}{\alpha E} \quad (4)$$

$$R = \frac{E}{\sigma_t^2(1 - \nu)} \quad (5)$$

Where E is the Young's modulus, ν is Poisson's ratio, α is the coefficient of thermal expansion, ΔT is the temperature difference, " a " is the dimension of the material involved in the study, k is the heat transfer conductivity of the material and h is the heat transfer coefficient. The sub-script " e " is the effective properties of the composite material, " c " denotes to critical and σ_t is the material's tensile strength.

For crack to be initiated, a composite material will have to reach the critical temperature difference (ΔT_c). The resulting critical induced thermal tensile stress ($\sigma_{ts,c}$) is given in Equation 3. The thermal shock resistance parameter (R) is equal to the critical

temperature difference (ΔT_c) of the material before crack is initiated, as presented in Equation 4 (Jones 2001). Also, crack propagation resistance (R') is dependent on available elastic energy in the material, as given in Equation 5 (Jones 2001).

RESULTS AND DISCUSSIONS

The results from this research work are presented in this section.

Multiple Inclusions Analysis: The study of multiple particle inclusions in a metal matrix composite was necessary because in practice composite materials have multiple inclusions. This study shed more light on the distribution of equal volume fraction of particles for multiple inclusions. The individual components of the composites are analysed and presented.

Particles Inclusion: Figs. 2 and 3, shows the distribution of the plots of stresses and strains against time. Figs. 2 and 3 showed that the stress and strain on the 10% particulate inclusions were higher than the other inclusions. In addition, there was a slight increase in the stresses and strains around the highest and lowest regions of the thermal cycle time.

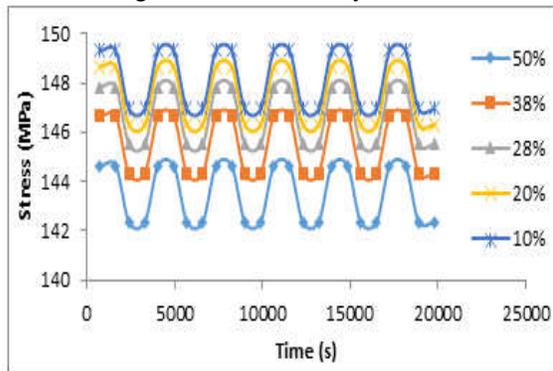


Fig. 2: Plots of particulate stress against time

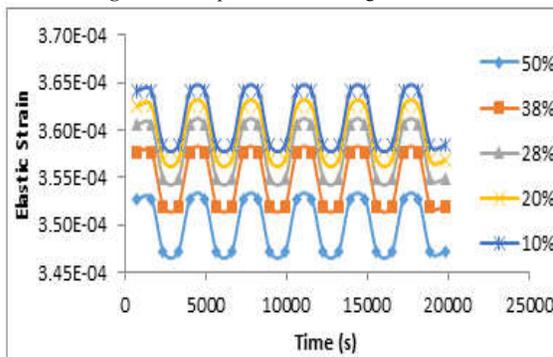


Fig. 3: Plots of particulate strain against time

Matrix: The plots of values for the stresses and strains of the matrix for 10-50% inclusions are presented in Figs. 4 and 5. Figs. 4 and 5 showed that 50% particle

inclusions recorded the lowest stresses and strains for the temperature profile studied. Likewise, 10% particulate inclusion recorded the highest stresses and strains.

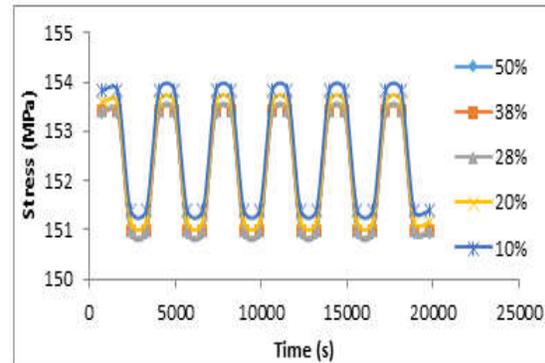


Fig. 4: Plots of stress against time for matrix

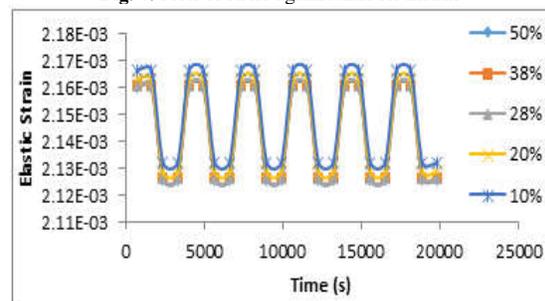


Fig. 5: Plots of strain against time for matrix

Multiple Inclusions Composites: Figs. 6 and 7 shows the stresses and strains of the composite material studied. In Fig. 6, it was observed that an increase in the percentage of inclusions reduces the stress of the composite material. In addition, the inclusions showed a significant reduction in the stresses as compared to the stresses of the matrix. The lowest stresses were recorded at 50% inclusion while the highest stresses were recorded at 10% inclusion. In Fig. 7, the strains were observed to be higher in the matrix as compared to the strains of the inclusions. However, there is only a slight difference in the strains of the matrix at the highest and lowest thermal cycle temperature. A similar behaviour was observed for the inclusions as well.

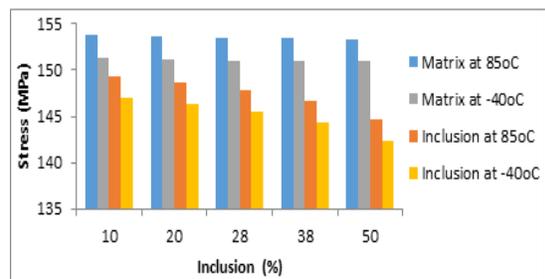


Fig. 6: Plots of stress against particulate inclusions

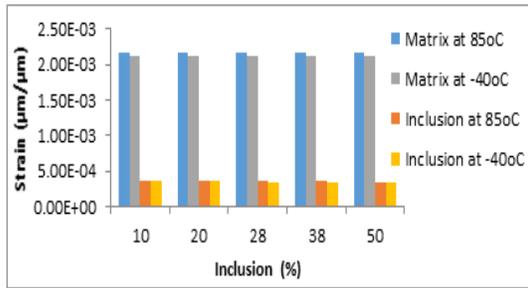


Fig. 7: Plots of strain against particulate inclusions

The deformations of the metal matrix composites for the multiple particle inclusions are presented in the form of contour plots in Fig. 8. Fig. 8 showed that majority of the metal matrix had low deformation as compared to the inclusion particles. In addition, the

bond area between the particle inclusions and the matrix had the highest amount of deformation. This will lead to delamination of the particle/matrix interface as shown in Fig. 9 (Zhang *et al* 2007). Also, it was observed that the deformation was affected by the arrangement of the particulate inclusions. Therefore, an evenly spaced inclusion is likely to have lower deformation than randomly spaced inclusions. This study showed that 50% inclusion recorded the lowest deformation. It could be inferred that the delamination between the inclusion particles and the matrix is a major issue affecting the production of composite materials for thermal management improvement in microelectronics applications. This issue could be reduced by increasing the number of particles in a composite material as shown in this study.

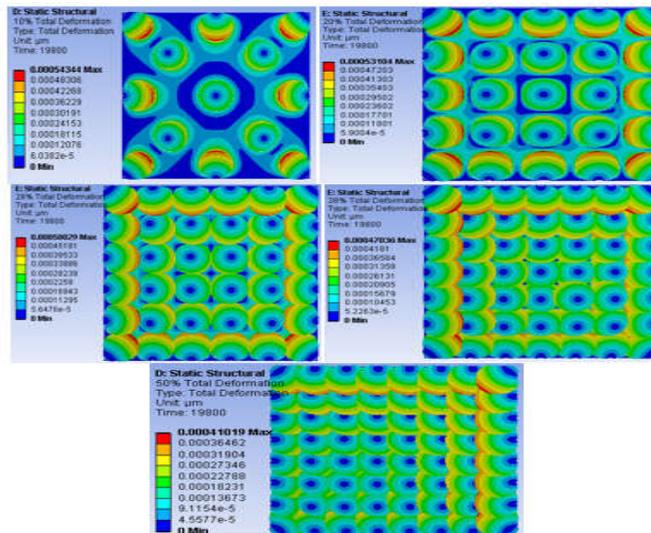


Fig. 8: Contour plots for the deformation of metal matrix composite for multiple inclusions

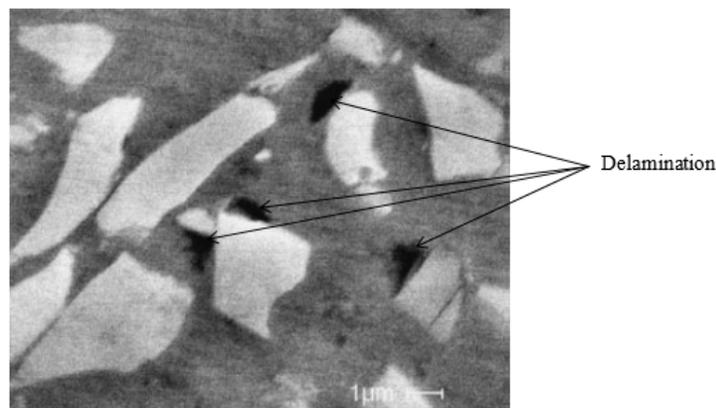


Fig. 9: Microstructure of deformed particles with arrows indicating the locations of the particle/matrix interface delamination (Zhang *et al* 2007)

Fatigue Life Prediction of AlSiC Composite Material: Jones (2001), stated that there is a power law relationship between cyclic thermo-mechanical stress and fatigue life. The material properties of the model used in this research is elastic. Therefore, the Basquin equation for fatigue life is used in the analysis (Balda 2009; Rohatgi *et al* 2007).

$$\sigma_a = \left(\frac{\Delta\varepsilon_e}{2}\right) E = \sigma_f' (2N_f)^b \quad (6)$$

$$N_f = \frac{1}{2} \left(\frac{\sigma_a}{\sigma_f'}\right)^{\frac{1}{b}} \quad (7)$$

Where σ_a is the stress amplitude (von-misses stress extrapolated from research), E is the modulus of elasticity, $\Delta\varepsilon_e/2$ is the elastic strain amplitude, σ_f' is the fatigue strength coefficient given as 558 MPa by (Rohatgi *et al* 2007), N_f is the number of cycles to failure, and b is the fatigue strength exponent (Basquin's exponent) which varies between -0.05 and -0.12 for most metals. The value of b used in the fatigue calculation is given as -0.1145 (Rohatgi *et al* 2007).

Fig. 10 presents the fatigue life of the multiple inclusions composite material. It was observed that as the percentage of inclusions were increased, the fatigue life of the composite material also increased. This conclusion is consistent with the results presented by Koh *et al* (1999). In addition, the 50% SiC particulate inclusions have the highest fatigue life (5.09E+04) as compared to the other percentage inclusions studied. While 10% particulate inclusions have the least fatigue life (4.39E+04) based on this study. Therefore, it is recommended that a composite material with 50% SiC inclusions will have better reliability for microelectronic heat sink used for commercial purpose.

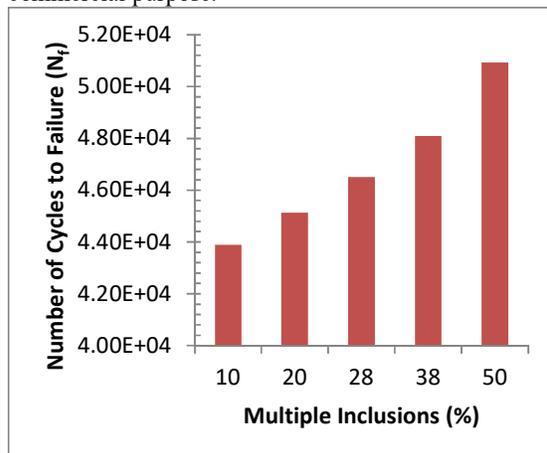


Fig. 10: Predicted life of AlSiC composite for multiple inclusions

Conclusions: This research showed the importance of representative volume element (RVE) in the development of composite materials. The stresses, strains, and deformations of the composite materials could be improved with increased particulate inclusions. The 50% AlSiC particulate inclusions are the most reliable composite material in this study because of its high number of cycles to failure. This study will be of assistance to manufacturers producing commercial heat sinks using composite materials.

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