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Nanomodeling of Nonlinear Thermoelastic Behavior of AA5454/ Silicon Nitride Nanoparticulate Metal Matrix Composites

Chennakesava R Alavala
Department of Mechanical Engineering, JNT University, Hyderabad-85

ABSTRACT
The aim of the present work was to estimate non-linear thermoelastic behavior of three-phase AA5454/silicon nitride nanoparticle metal matrix composites. The thermal loading was varied from subzero temperature to under recrystallization temperature. The RVE models were used to analyze thermo-elastic behavior. The AA5454/silicon nitride nanoparticle metal matrix composites have gained the elastic modulus below 0^oC and lost at high temperatures.
Keywords **-** AA5454, finite element analysis, RVE model, silicon nitride, thermoelastic.

I. INTRODUCTION

Metal matrix composites offer enhanced properties such as higher strength, stiffness, damping capacity and weight savings. The use of silicon carbide [1-5] and alumina [6-11] were dealt as a reinforcement particulate in most of the metal matrix composites. Al-alloys [12] and Mg-alloys [13] were employed as matrix materials in the metal matrix composites intended for automotive applications. Silicon nitride has the best combination of mechanical, thermal and electrical properties of any advanced technical ceramic material. Its high strength and toughness make it the material of choice for automotive and bearing applications. AA5454 aluminum alloy is commonly used in welded structures such as pressure vessels and ships. The dimensional stability is very important at high operating temperatures [14, 15]. Because the constituents usually have very different stiffness and coefficients of thermal expansion (CTE), the internal stress inhomogenity can rapidly increase even under a low level of external applied loads or changes in the environmental temperature [16]. Therefore, it is necessary to understand the thermo-elastic behavior of AA5454/Si_3N_4 nanoparticulate metal matrix composites.

Finite element method (FEM) is applied to estimate the local response of the material using unit cell reinforced by a single particle subjected to periodic and symmetric boundary conditions [17-19]. The aim of the present work was to assess the nonlinear thermoelastic behavior of AA5454/Si_3N_4 nanoparticulate metal matrix composites. The RVE models were used to analyze the AA5454/Si_3N_4 nanoparticulate metal matrix composites with interphase between them using finite element analysis.

II. MATERIALS AND METHODS

The matrix material was AA5454 aluminum alloy. The reinforcement material was Si3N4 nanoparticles of average size 100nm. The mechanical properties of materials used in the present work are given in table 1. The composites were prepared by the stir casting technology and pressure die casting process [4, 8]. The volume fractions of Si3N4 nanoparticles were 10% and 30%. The as-cast samples were heat treated under H34 conditions. The tensile properties were established as per ASTM D3039 standard test procedure.

Table 1. Mechanical properties of AA5454 matrix and Si_3N_4 nanoparticles

Property	AA5454	Si_3N_4
Density, g/cc	2.69	3.31
Elastic modulus, GPa	70.3	317
Ultimate tensile strength, MPa	303	397
Poisson’s ratio	0.33	0.23
CTE, μm/m-^oC	21.9	3.4
Thermal Conductivity, W/m-K	134.0	27.0
Specific heat, J/kg-K	900	170

In this research, a square RVE (Fig.1) was implemented to analyze the thermo-elastic (compressive) behavior AA5454/ Si_3N_4 nanocomposites. The large strain PLANE183 element was used in the matrix and the interphase regions in all the models. In order to model the interphase between nanoparticle and matrix, a CONTACT172 element was used. The maximum contact friction stress of $\sigma_y/\sqrt{3}$ (where, σ_y is the yield stress of the material being deformed) was applied at the contact surface. The basic Coulomb friction model was considered between two contacting surfaces. Both uniform thermal and hydrostatic pressure loads were applied simultaneously on the RVE model.

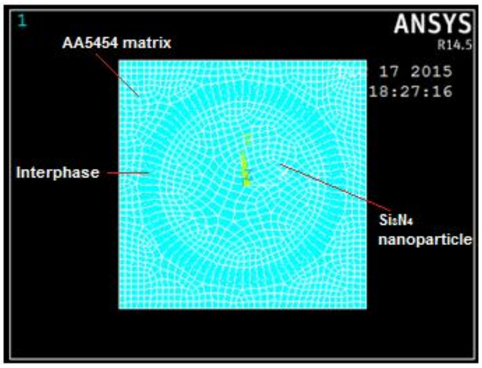

Fig.1. Square RVE containing a nanoparticle.

III. RESULTS AND DISCUSSION

The finite element analysis (FEA) was carried out at sub-zero and high temperature conditions. The hydrostatic pressure load was applied RVE model to investigate thermo-elastic tensile behavior of AA5454/Si_3N_4 nanoparticulate composites. The volume fractions of Si_3N_4 nanoparticles in the AA5454 matrix were 10% and 30%.

3.1 Thermoelastic Behavior

Elastic and thermo-elastic strains as a function of temperature are shown in Fig.2. The thermo-elastic strain increased with increase of temperature (Fig.2b). The thermo-elastic strain was very high at 300°C for the composites having 10% Si_3N_4. For composites with low volume fraction (10%) of Si_3N_4, the elastic strain decreased from -300°C to 0°C and again it increased from 0°C to 300°C (Fig.2a). For composites with high volume fraction (30%) of Si_3N_4, the elastic strain increased from -200°C to 300°C. The basic reason could be the CTE mismatch of 18.5 µm/m-°C between AA5454 alloy and Si_3N_4.

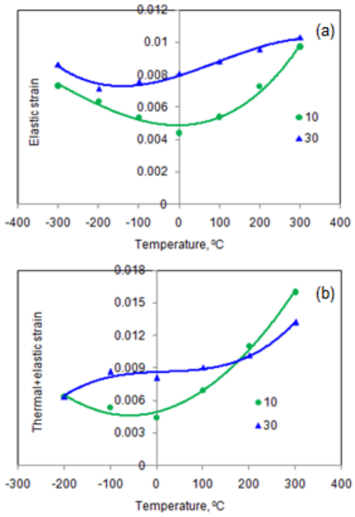

Fig. 2. Influence of temperature on elastic and thermo-elastic strains.

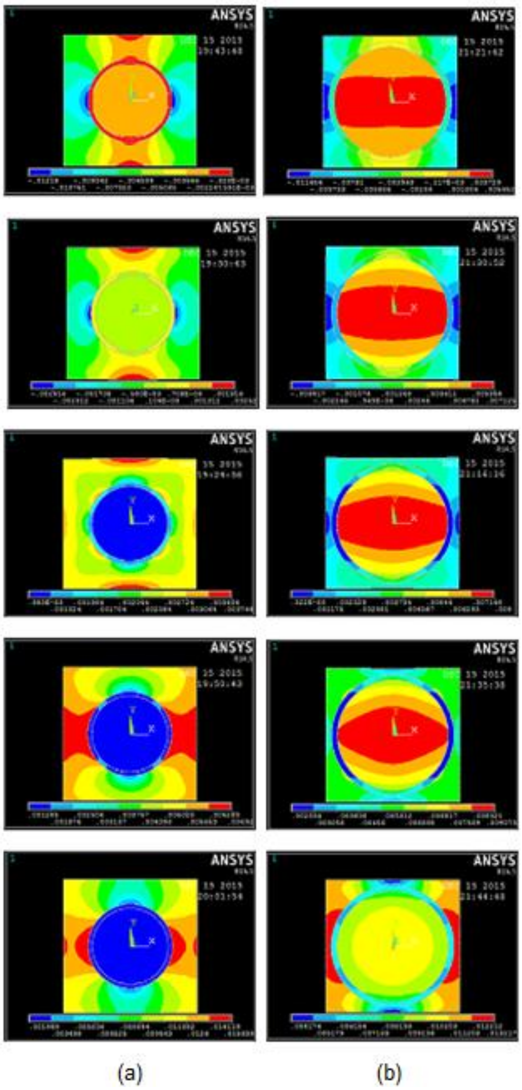

Fig. 3. Elastic (a) and thermo-elastic (b) strains developed in composites with 10%Vp nanoparticles.

Fig.3 demonstrates the state of elastic and thermo-elastic strains developed in the AA5454/ 10%Si_3N_4 composites. Fig. 4 demonstrates the state of elastic and thermo-elastic strains developed in the AA5454/ 30%Si_3N_4 composites. In all the cases, Si_3N_4 nanoparticles had experienced the compressive stains below 0°C in the counter direction of tensile loading and above 0°C in the normal direction of the loading [14]. For Si_3N_4 nanoparticles the CTE is lower than that of AA5454 matrix.

The tensile strength decreased with increase of temperature from -300 °C to 0°C for both the volume fractions of 10% and 30% Si_3N_4 (Fig. 5). However, the tensile strength increased with the increase of temperature for the composites having volume fraction of 10% Si_3N_4 0 °C to 300°C. This might be due to the dominant role of AA5454 matrix extending the yield point and elongation. But, the influence of temperature (from 0 °C to 300°C) was continued for the composites having volume fraction of 30% Si_3N_4 as that prevailed from -300 °C to 0°C. The tensile strength increased with increase of volume fraction of Si_3N_4. The raster images of tensile strength are shown in Fig. 6 for clear understanding the penalty of temperature on the tensile strength.

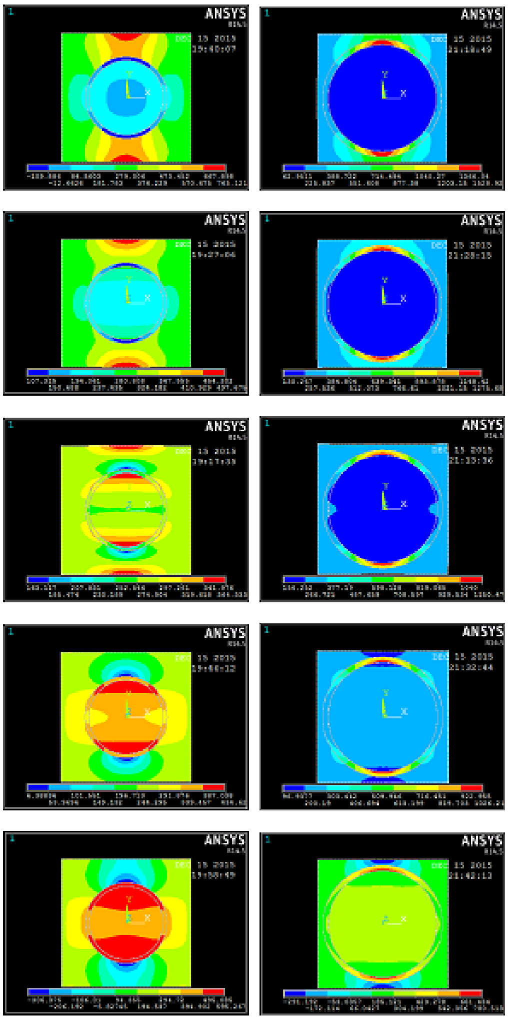

Fig. 4. Elastic (a) and thermo-elastic (b) strains developed in composites with 30%Vp nanoparticles.

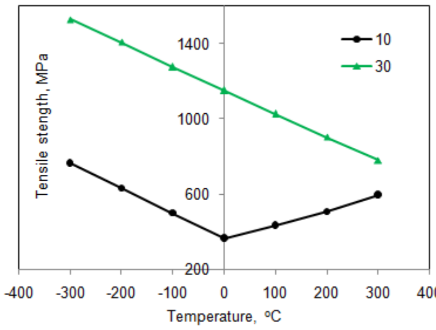

Fig. 5. Effect of temperature and volume fraction of Si_3N_4 on tensile strength.

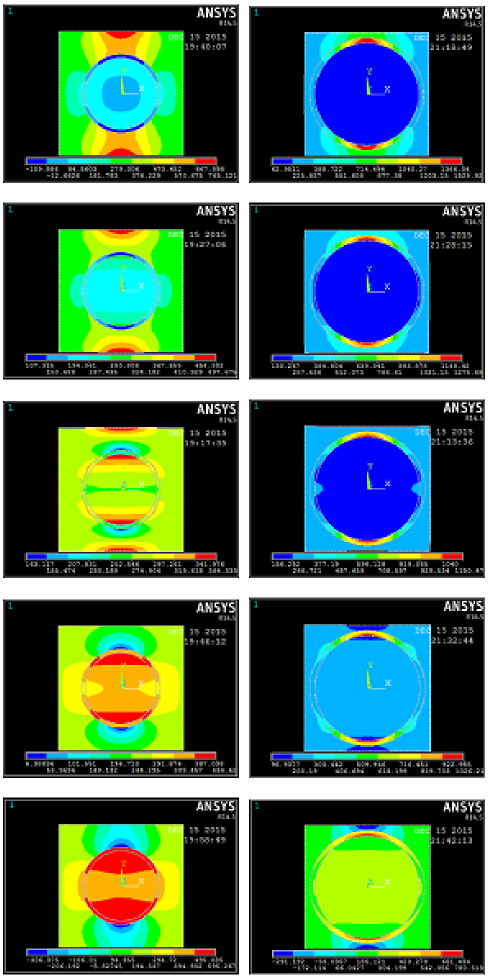

Fig. 6. Tensile strength induced in composites with (a) 10% and (b) with 30%Vp nanoparticles.

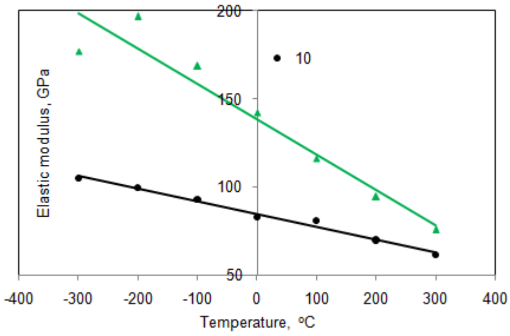

Fig. 7. Effect of temperature and volume fraction of Si_3N_4 nanoparticles on the elastic modulus.

The effect of temperature and volume fraction of Si_3N_4 nanoparticles on elastic modulus is shown in Fig. 7. It was observed that the effective elastic modulus of the composite increased with higher particle volume fraction and decreased with increase of temperature. The gain in the elastic modulus was observed below 0°C on account of increase in the stiffness of the composites (Fig. 8). The loss in the elastic modulus was observed below 0°C on account of decrease in the stiffness of the composites.

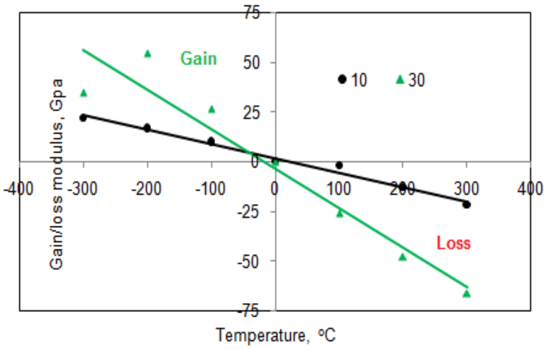

Fig. 8. Effect of temperature and volume fraction of Si_3N_4 nanoparticles on loss and gain of the elastic modulus.

3.2 Fracture Behavior

The von Mises stress decreased with the increase of temperature increased from -300°C to 300°C (Fig. 9) for the composites having 30% Si_3N_4. This phenomenon was appeared from -300°C to 0°C for the composites having 10% Si_3N_4. This trend was inverse from -300°C to 0°C for the composites having 10% Si_3N_4. Within the nanoparticle various contours were also observed due to CTE mismatch between Si_3N_4 nanoparticle and AA5454 matrix. It was also noted that the maximum stress field in the vicinity of interphase was up to three to four times higher than that far away from the nanoparticle–matrix interfaces (Fig. 10). This implies a potential early debonding [20, 21]. At the subzero temperatures, the maximum stress field was in the normal direction of tensile loading. As the temperature increased ductile mode of failure was witnessed in the composites. Some structural changes were also locally occurred in the Si_3N_4 nanoparticle. Below 0°C, the Si_3N_4 nanoparticle was elongated in the normal direction of tensile loading while it was elongated in the direction of loading. At subzero temperature the failure mode was brittle in nature. The room temperature fracture in the AA5454/Si_3N_4 can be seen in Fig. 11.

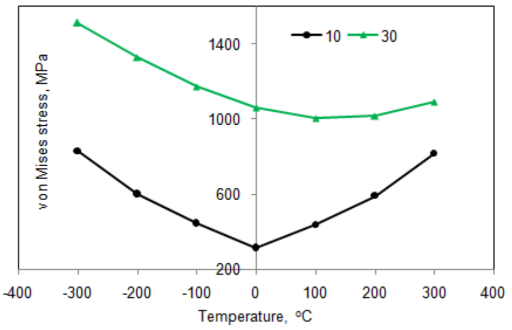

Fig.9. Effect of temperature and volume fraction of Si_3N_4 nanoparticles the von Mises stress.

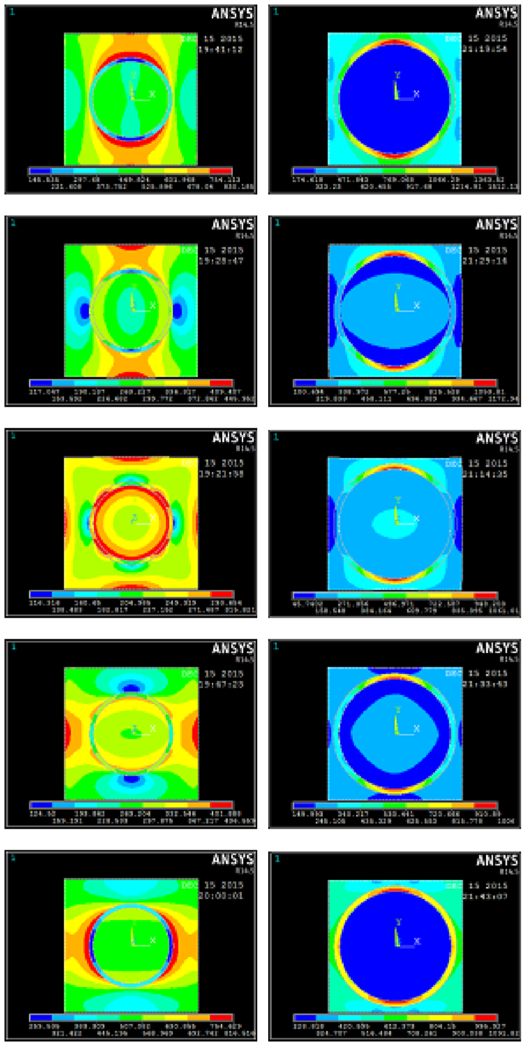

Fig. 10. Von Mises stress induced in the composites.

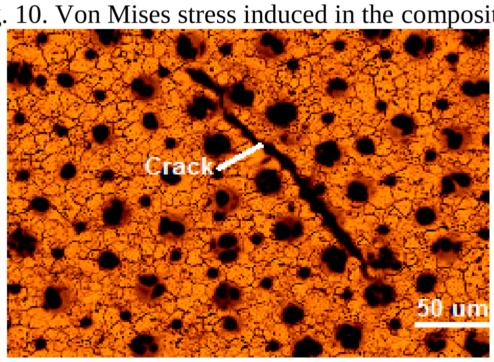

Fig. 11. Fracture mode in AA5454/ Si_3N_4 composites.

IV. CONCLUSION

The thermo-elastic strain increased with increase in the temperature of AA5454/ Si_3N_4 metal matrix composites except for low volume fraction of Si_3N_4. As the temperature increased, the maximum stress occurred in the interphase region between the matrix AA5454 and Si_3N_4. The effective elastic modulus of the composite increased with higher particle volume fraction and decreased with increase of temperature.

There was gain in the elastic modulus below 0°C and loss of it above 0°C.

Acknowledgements

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