Combined Loading and Micromechanical Analysis of AA5050 Alloy-Silicon Oxide Particle-Reinforced Metal Matrix Composites

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Abstract: *In the present work, the AA5050-SiO_2 metal matrix composites were manufactured at 10% and 30% volume fractions of SiO_2. The composites were subjected to mechanical and thermal loads. The microstructure of AA5050 alloy-SiO_2 reveals the fracture of interphase and particle. The particle fracture was initiated before the transformation from α-quartz to beta-quartz took place at 573°C due to combined thermal and tensile loading.*

Keywords: *AA5050, silicon oxide, spherical nanoparticle, RVE model, finite element analysis, interphase fracture.*

1. INTRODUCTION

Incorporation of hard second phase particles in the alloy matrices to produce metal matrix composites has been reported to be more beneficial and economical due to its high specific strength and corrosion resistance properties. In the past, various research works have been carried out on metal matrix composites prepared from aluminum alloy matrices and reinforced particles such as SiC [1-7], Al_2O_3 [8-12], TiO_2 [13-15], ZrO_2 [16], TiN [17], B_4C [18] ZrC [19], $Al(OH)_3$ [20] and graphite [21-22]. Reliable usage of such a material depends on an accurate understanding of the elastic and elastic-plastic behavior under different types of loading. Thermal shock and thermal cycling are the life-limiting factors for components exploitable in rapidly changing thermal conditions and high-temperature materials. In particular, the stress transfer characteristic of nanoparticle reinforced composite materials under various mechanical and thermal loadings is very important for optimum utilization of metal matrix composites. The characteristics of low density and low thermal expansion of ceramics assume a great deal of importance in most applications.

Finite element method (FEM) is capable of identifying the local response of the material. A common practice to estimate the bulk and local responses of composite material is to use a unit cell reinforced by a single fiber, whisker or particle subjected to periodic and symmetric boundary conditions [23]. A lot of research was carried out to assess the interface behavior in particle reinforced metal matrix composites under tensile loading using finite element analysis approach [14-20].

Silicon dioxide is also known as silica. The Si atom shows tetrahedral coordination, with 4 oxygen atoms surrounding a central Si atom (figure 1). The only stable form under normal conditions is α-quartz. The density of stishovite is 4.287 g/cc, which compares to α-quartz, the densest of the low-pressure forms, which has a density of 2.648 g/cc. The difference in density can be ascribed to the increase in coordination as the six shortest Si-O bond lengths in stishovite (four Si-O bond lengths of 176 pm and two others of 181 pm) are greater than the Si-O bond length (161 pm) in α-quartz. The applications of SiO_2 include nanocomposites of silica.

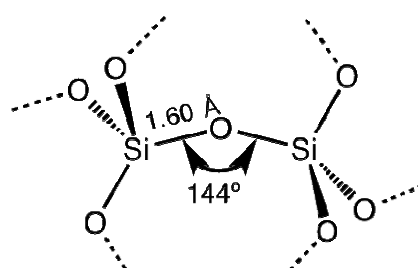


Figure 1: Structure of SiO_2.

In the present work, the effect of thermo-mechanical loading on the fracture in AA5050 alloy/SiO_2 composites was examined. Both microscopic and micromechanics methods were employed to assess fracture in the composites. ANSYS software was used to computationally simulate thermo-mechanical nonlinear behavior of AA5050 alloy/SiO_2 composites to analyze local constituent response including the interface/interphase regions. The results obtained from the numerical simulation were validated with the experimental results.

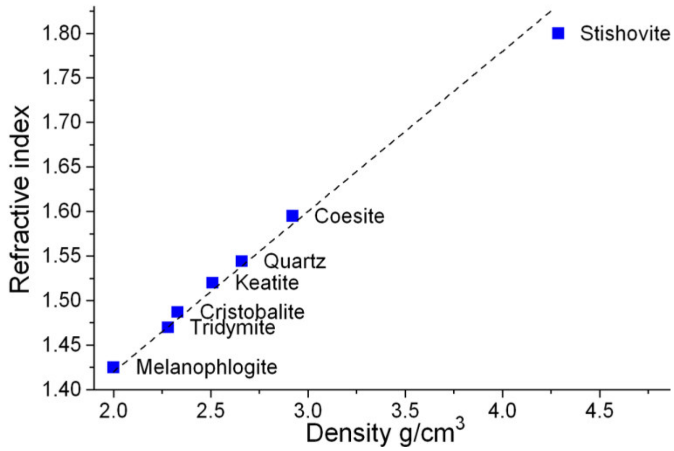


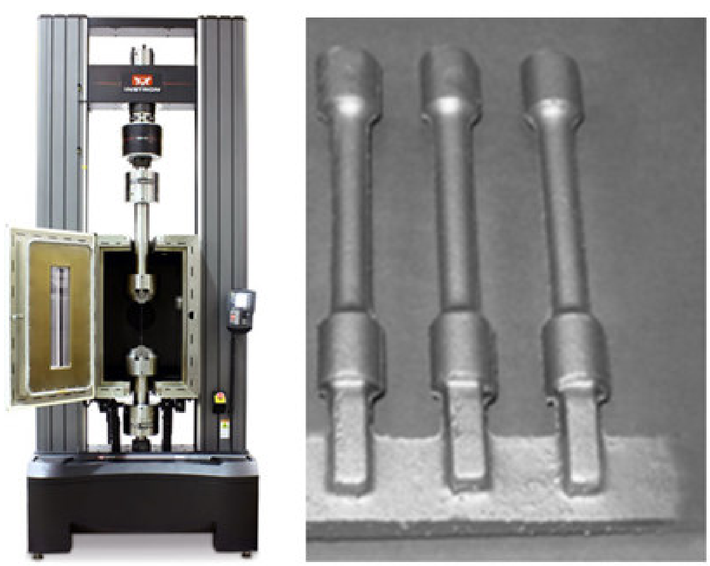
Figure 2: Relation between refractive index and density for some SiO_2 forms.

2. MATERIALS METHODS

The matrix material was AA5050 alloy. The reinforcement material was SiO_2 nanoparticles of average size 100nm. The mechanical properties of materials used in the present work are given in table 1.

Table 1: Mechanical properties of AA5050 matrix and SiO_2 nanoparticles

Property	AA5050	SiO_2
Density, g/cc	2.69	6.73
Elastic modulus, GPa	68.9	430.0
Coefficient of thermal expansion, 10^{-6} 1/^{o}C	21.8	6.8
Specific heat capacity, J/kg/^{o}C	900	368
Thermal conductivity, W/m/^{o}C	193	25
Poisson's ratio	0.33	0.25



(a) (b)

Figure 2: Tensile testing: UTM with temperature controlled chamber and (b) As-cast tensile specimens.

AA5050 alloy/ SiO_2 composites were fabricated by the stir casting process and low pressure casting technique with argon gas at 3.0 bar. The composite samples were give solution treatment and cold rolled to the predefined size of tensile specimens. The heat-treated samples were machined to get cylindrical specimens (figure 2) for the tensile tests. The tensile specimens were placed in the grips of a Universal Test Machine (UTM) with temperature controlled chamber at a specified grip separation and pulled until failure. The test speed was 2 mm/min. A strain gauge was used to determine elongation. In the current work, a cubical representative volume element (RVE) was implemented to analyze the tensile behavior AA5050/Z SiO_2 nanoparticle composites at two (10% and 30%) volume fractions of SiO_2 and at different temperatures. The shape SiO_2 nanoparticle considered in this work is spherical. The periodic particle distribution was a square array and corresponding representative volume element (RVE) as shown in figure 3. The large strain PLANE183 element was used in the matrix in all the models. In order to model the adhesion between the matrix and the particle, a CONTACT 172 element was used.

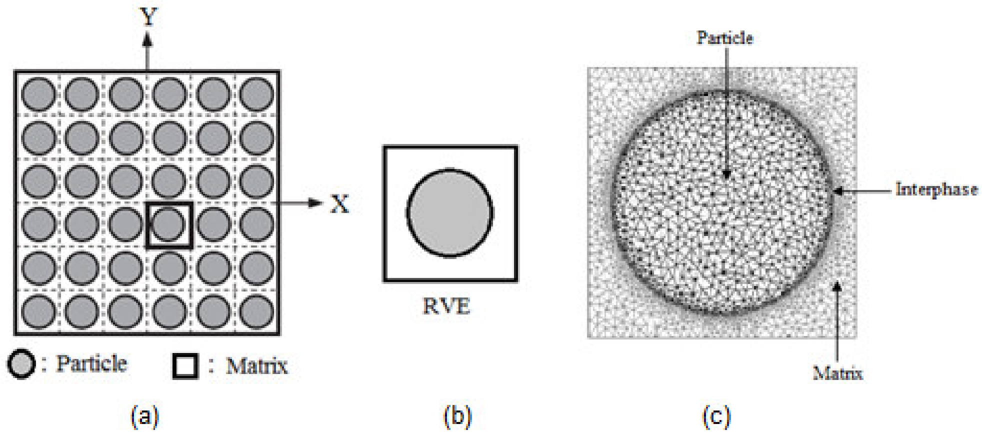


Figure 3: Square array of particles (a), Representative volume element (b) and Discretization of RVE (c).

3. RESULTS AND DISCUSSION

3.1 Thermo-Mechanical Behavior

Figure 5 represents micromechanical properties of AA5050/ SiO_2 composites. The elastic modulus is normalized with the elastic modulus of AA5050 alloy. The normalized stiffness of the composites decreases with increase of temperature. The stiffness of AA5050 alloy/30% SiO_2 composites is higher than that of AA5050 alloy/10% SiO_2 composites. The normalized stiffness along the normal direction is lower than that along the load direction. The normalized shear modulus is constant with increase of temperature for AA5050 alloy/30% SiO_2 composites; but it decreases above 200°C for AA5050 alloy/10% SiO_2 composites (figure 5b). The major Poisson's ratio increases with temperature (figure 5c).

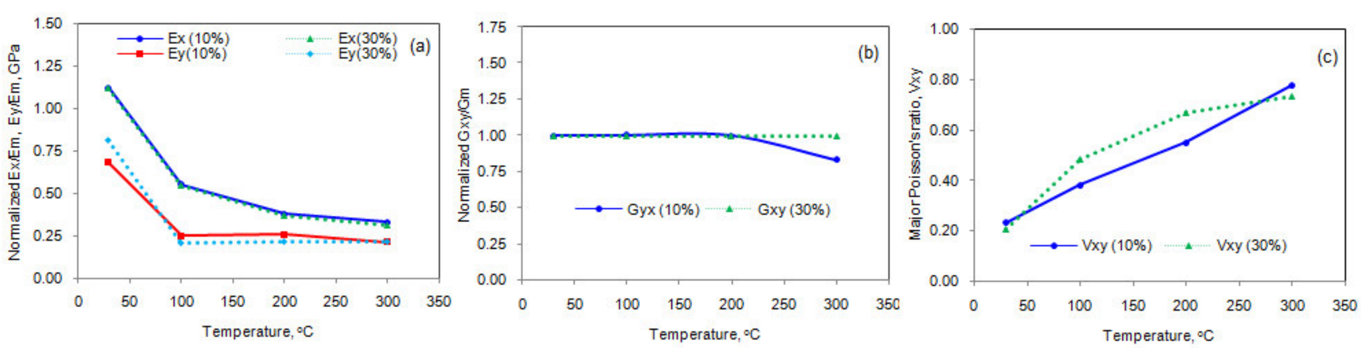


Figure 5: Effect of volume fraction on micromechanical properties of AA5050/ SiO_2 composites.

3.2 Fracture Analysis

If the particle deforms in an elastic manner (according to Hooke's law) then,

$$\tau = \frac{n}{2}\sigma_p \qquad (1)$$

where σ_p is the particle stress. If particle fracture occurs when the stress in the particle reaches its ultimate tensile strength, $\sigma_{p,uts}$, then setting the boundary condition at

$$\sigma_p = \sigma_{p,\,uts} \qquad (2)$$

The relationship between the strength of the particle and the interfacial shear stress is such that if

$$\sigma_{P,uts} < \frac{2\tau}{n} \quad (3)$$

Then the particle will fracture. From the figure 6a, it is observed that the SiO_2 nanoparticle was fractured as the condition in Eq. (3) is satisfied above 275°C and 150°C for the composites AA5050/10% SiO_2 and AA5050/30% SiO_2 composites, respectively. This is due to CTE and stiffness mismatches between SiO_2 nanoparticles and AA5050 alloy matrix. For the interfacial debonding/yielding to occur, the interfacial shear stress reaches its shear strength:

$$\tau = \tau_{max} \quad (4)$$

For particle/matrix interfacial debonding can occur if the following condition is satisfied:

$$\tau_{max} < \frac{n\sigma_P}{2} \quad (5)$$

It is observed from figure 6b that the interphase debonding occurs between SiO_2 nanoparticle and AA5050 alloy matrix as the condition in Eq.(5) is satisfied at all temperatures for the composites AA5050/10% SiO_2 composites and above 200°C for the composites AA5050/30% SiO_2. The debonding phenomenon is high in the composites comprising of 10% SiO_2.

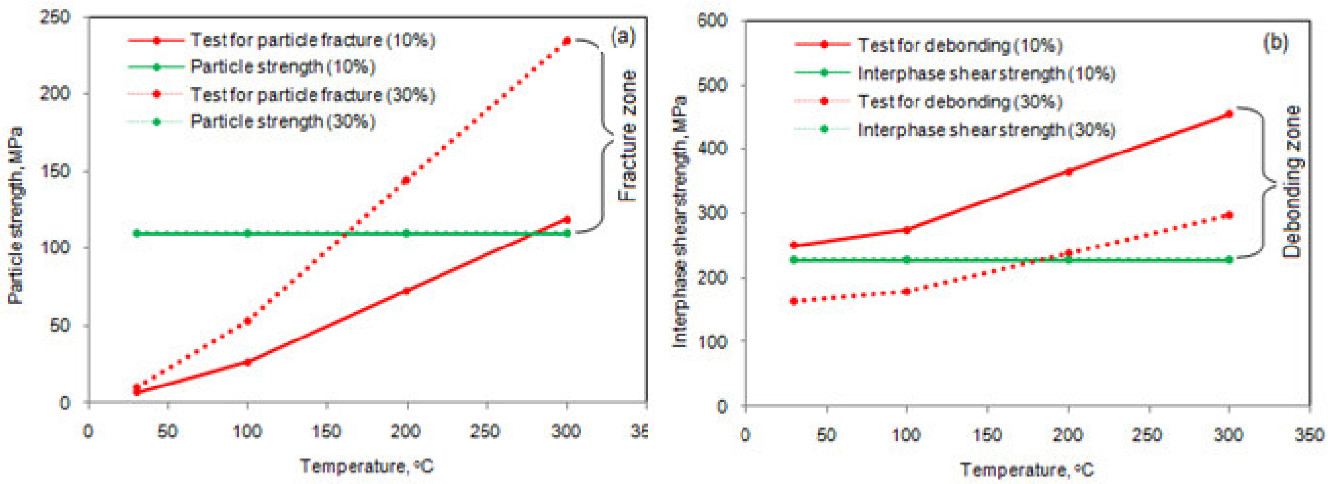


Figure 6: Criterion for interfacial debonding (a) and for particle fracture (b).

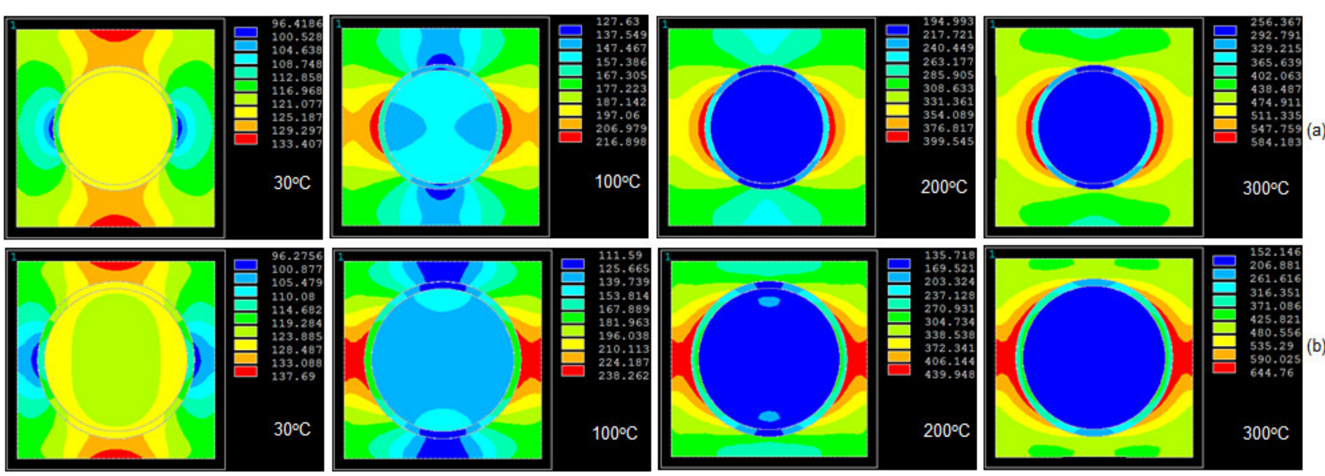


Figure 7: Images of von Mises stresses obtained from FEA: (a) AA5050/10% SiO_2 and (b) AA5050/30% SiO_2 composites.

The von Mises stress induced at the interface are higher than that induced in the nanoparticle (figure 7). Hence, the interfacial interphase fracture was occurred between the particle and the matrix. The particle fracture is initiated in AA5050/30% SiO_2 composites at 200°C of thermal loading and in AA5050/ 10% SiO_2 composites at 30°C of thermal loading, respectively, due to thermal shock. The microstructure shown in figure 8 confirms the occurrence of interphase and particle fractures in the composites. The transformation from α-quartz to beta-quartz takes place abruptly at 573 °C. Since the transformation is accompanied by a significant change in volume it can easily induce fracturing of SiO_2. Even though the temperature is below 573°C, the

SiO_2 nanoparticle fracture was occurred because of combined thermal and tensile loading. Hence, the particle fracture was initiated well below 573°C.

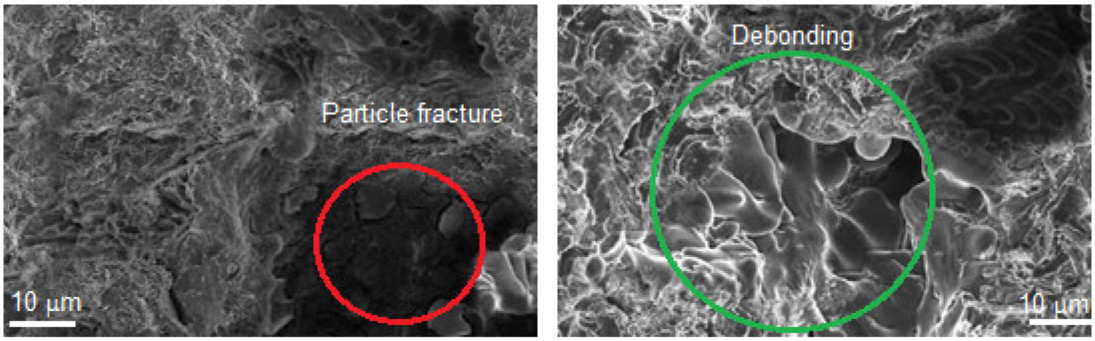


Figure 8: SEM images showing particle fracture and interphase debonding.

4. CONCLUSION

The shear stress is high at the interface resulting to interphase debonding in AA5050/ SiO_2 composites. The particle fracture is also initiated at 30°C and 200°C of thermal loading of AA5050/ 10% SiO_2 and AA5050/ 30% SiO_2 composites, respectively. The microstructure obtained from the experimental samples confirms the fracture of interphase between the SiO_2 particles and AA5050 alloy matrix and particle fracture.

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