Estimation of Fracture in Zirconia/AA2024 Alloy Particle-Reinforced Composites Subjected to Thermo-Mechanical Loading

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Abstract: *In the present work, the AA2024/ZrO_2 metal matrix composites were fabricated at 10% and 30% volume fractions of ZrO_2. The composites were subjected to structural and thermal loads. The microstructure of AA2024 alloy/ZrO_2 reveals uniform distribution of ZrO_2 in the AA2024 alloy matrix. The transformation of ZrO_2 has not occurred from monoclinic to tetragonal due to thermal loading. Only interphase fracture has taken place in the composites.*

Keywords: *AA2024, zirconia, spherical nanoparticle, RVE model, finite element analysis, debonding.*

1. INTRODUCTION

Many of the problems of special interest in the micromechanics domain are related to inclusions that are dispersed into an otherwise continuous phase. Of particular interest here are the cases of improving or optimizing stiffness and strength. Due to processing conditions and various surface treatments on the reinforced particles, an interfacial region is created between the particle and matrix in a particle reinforced composite material. In other words, a compliant bond almost always exists between the particle and the matrix. This region is of primary importance because it affects the quality of bonding and hence influences the structural performance of the overall composite material. The characterization of the interphase between the fiber and the matrix can be accomplished using either microscopic or micromechanics techniques, depending upon the dimensions as well as the type of composite system. Several microscopic techniques have been found to successfully characterize the interphase region. This includes destructive methods such as scanning electron microscope (SEM), scanning acoustic microscopy (SAM) [1]. It is known that many micromechanics models have been proposed to predict the effective mechanical properties of two-phase composites, such as the Mori–Tanaka model, differential method and generalized self-consistent method [2, 3]. The solution of one inclusion problem is the basis of these micromechanics models. However, the thickness of the thin interphase may become comparable to the size of the fillers for some cases, for example, where the fillers are nanoscale particles. Computational methods using finite element methods are the effective ways to study the micromechanical behavior of composite materials [4-20].

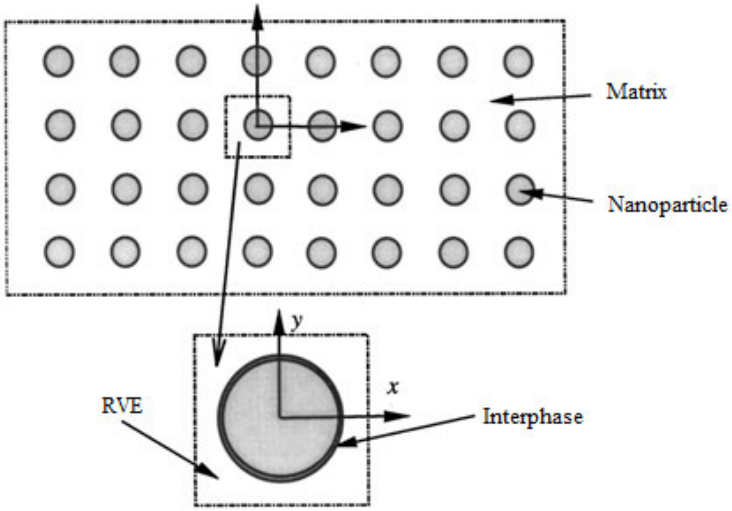

Figure 1: The interphase in a nanoparticle-reinforced composite.

Zirconia Powder (Zirconium Oxide, ZrO_2) is synthesized from zircon sand ($ZrO_2 \cdot SiO_2$) using a solid-state reaction process. Zirconia has the common characteristics of ceramics that are not found in metallic or organic materials, including high

hardness (next to diamond), high mechanical strength, low coefficient of friction, high temperature stability, chemical resistance, erosion resistance, low electrical conductivity. Zirconium dioxide, ZrO_2, is used for optical coatings. Dense layers with exceptional hardness can be deposited by electron-beam evaporation or sputtering. Because of its hardness, it also finds common use as an abrasive material. In this paper, the effect of temperature on the fracture in AA2024 alloy/ZrO_2 composites was investigated. The shape ZrO_2 nanoparticle considered in this work is spherical. The periodic particle distribution was a square array as shown in figure 1. Both microscopic and micromechanics methods were employed in this paper.

2. MATERIALS METHODS

The matrix material was AA2024 alloy. The reinforcement material was ZrO_2 nanoparticles of average size 100nm (figure 2). The mechanical properties of materials used in the present work are given in table 1.

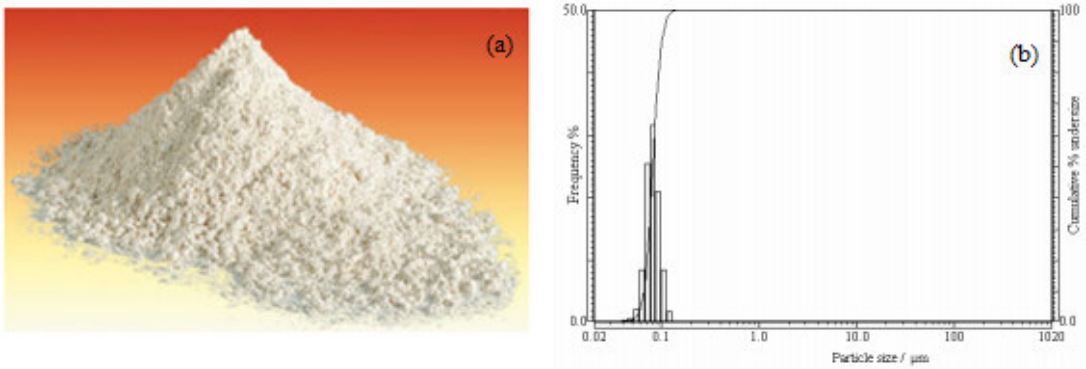

Figure 2: Zirconia nanopowder (a) and particle distribution (b).

Table 1: Mechanical properties of AA2024 matrix and ZrO_2 nanoparticles

Property	AA2024	ZrO_2
Density, g/cc	2.71	5.5
Elastic modulus, GPa	72.49	250.0
Coefficient of thermal expansion, 10^{-6} 1/^oC	20.8	7.5
Specific heat capacity, J/kg/^oC	880	540
Thermal conductivity, W/m/^oC	134	2.7
Poisson's ratio	0.33	0.32

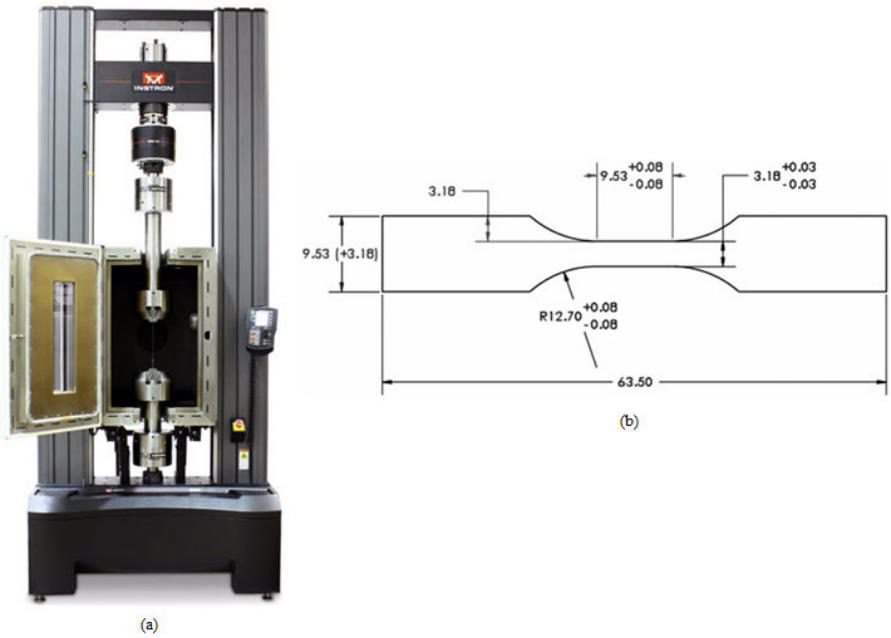

Figure 3: Tensile testing: UTM with temperature controlled chamber and (b) shape and dimensions of tensile specimen.

AA2024 alloy/ ZrO_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 flat-rectangular specimens (figure 3) 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 AA2024/ ZrO_2 nanoparticle composites at two (10% and 30%) volume fractions of ZrO_2 and at different temperatures. 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.

3. RESULTS AND DISCUSSION

The optical micrograph as shown in figure 4 reveals random distribution of ZrO_2 particles in AA2024 alloy matrix.

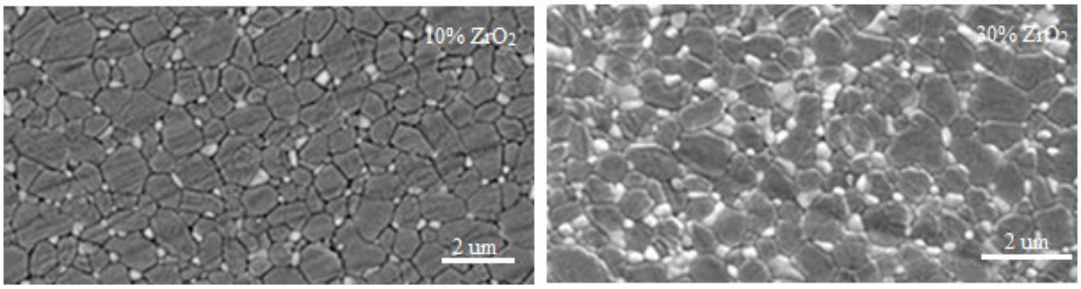

Figure 4: Microstructure showing distribution of ZrO_2 nanoparticles in AA2024 alloy matrix.

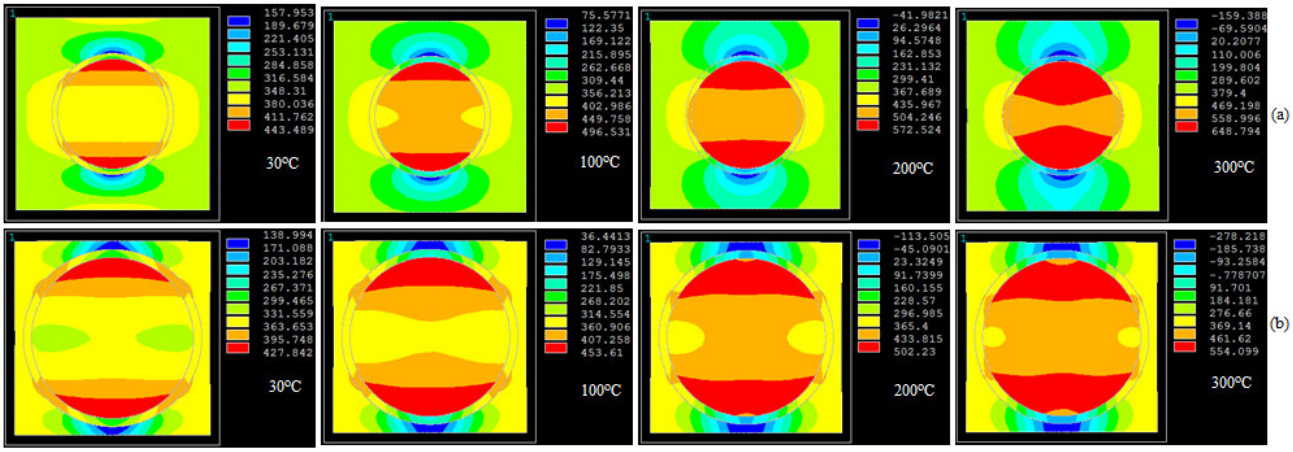

Figure 54: FEA results of tensile stress induced along load direction in the composites comprising of: (a) 10% ZrO_2 and (b) 30% ZrO_2.

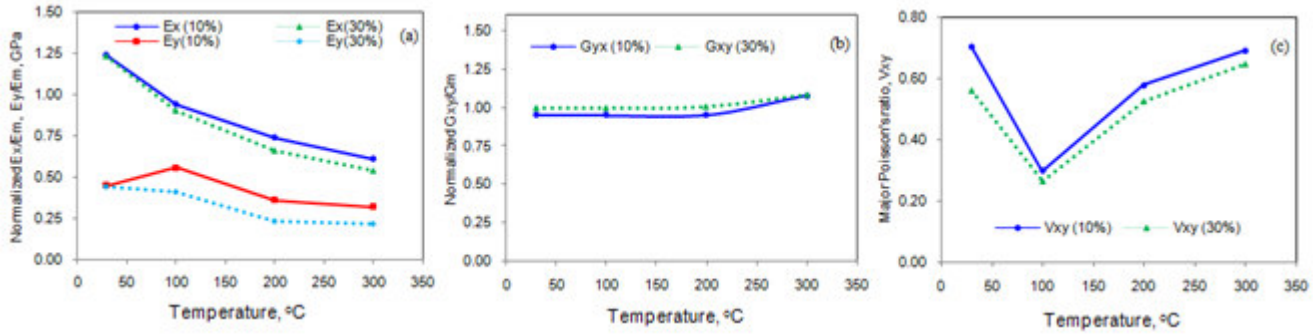

Figure 6: Effect of temperature on stiffness of AA2024/ZrO_2 composites.

3.1 Thermo-Mechanical Behavior

Figure 5 represents the tensile stresses induced in the AA2024/ZrO_2 composites along the load direction. The tensile stress increases with increase of temperature and it decreases with increase of volume fraction of AA2024/ZrO_2 in AA2024 alloy

matrix. This is due to softening of the composite with increase of temperature. The normalized elastic modulus is shown in figure 6a. The elastic modulus is normalized with the elastic modulus of AA2024 alloy. The stiffness of the composites decreases with increase of temperature. The stiffness of AA2024 alloy/10% ZrO_2 composites is higher than that of AA2024 alloy/30% ZrO_2 composites with respect to increase of temperature. The normalized stiffness along the normal direction is lower than that along the load direction. The normalized shear modulus increases with volume fraction of ZrO_2 (figure 6b). Initially, the major Poisson's ratio decrease from 30°C to 100°C and later on it increases with temperature from 100°C to 300°C (figure 6c).

3.2 Fracture Analysis

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

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

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

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

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 7b, it is observed that the ZrO_2 nanoparticle was not fractured as the condition in Eq. (3) is not satisfied. 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 7a that the interfacial debonding occurs between ZrO_2 nanoparticle and AA2024 alloy matrix as the condition in Eq.(5) is satisfied. This is due to CTE mismatch between ZrO_2 nanoparticles and AA2024 alloy matrix.

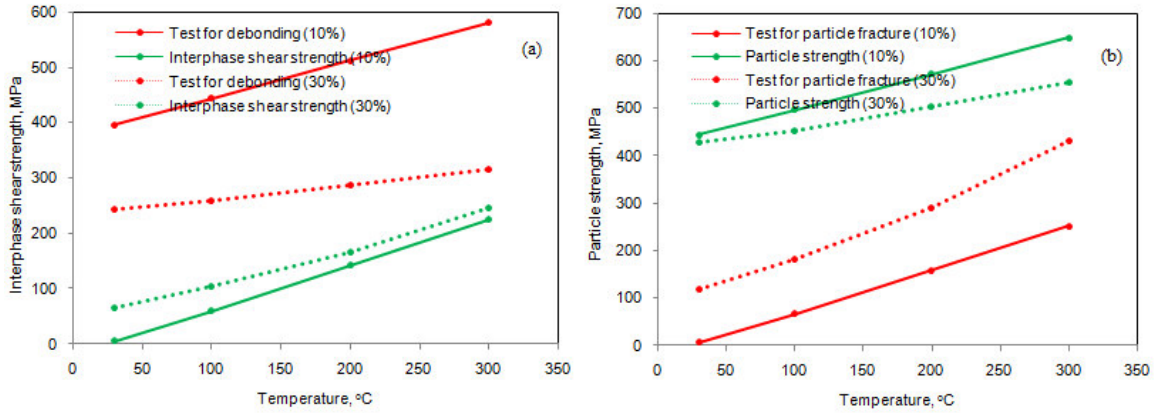

Figure 7: Criterion for interfacial debonding (a) and for particle fracture (b).

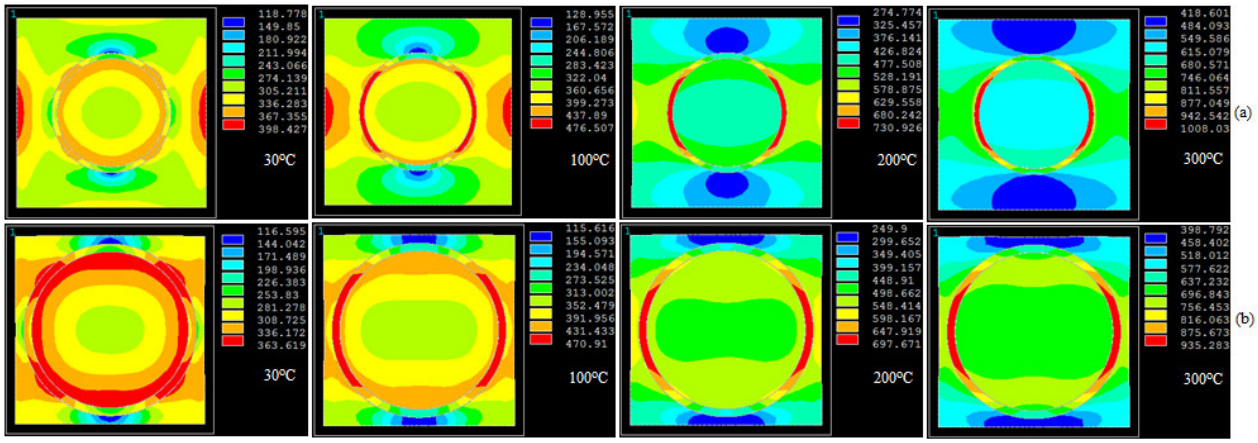

Figure 8: Images of von Mises stresses obtained from FEA: (a) AA2024/10% ZrO_2 and (b) AA2024/30% ZrO_2 composites.

The von Mises stress induced at the interface are higher than that induced in the nanoparticle (figure 8). Hence, the interfacial debonding was occurred between the particle and the matrix. The interfacial debonding increases with increase of temperature. Pure zirconium dioxide undergoes a phase transformation from monoclinic (stable at the room temperature) to tetragonal (at about 1173 °C) and then to cubic (at about 2370 °C), according to the scheme:

monoclinic (1173 °C) ↔ tetragonal (2370 °C) ↔ cubic (2690 °C) ↔ melt

As the test temperature is well below 1173°C, the transformation of ZrO_2 is not issue in the present work.

4. CONCLUSION

The microstructure of AA2024 alloy/ ZrO_2 composites reveals the random distribution of ZrO_2 nanoparticles in the matrix. The shear stress is high at the interface resulting to interfacial debonding in AA2024/ ZrO_2 composites. The transformation of zirconia has not taken place from monoclinic to tetragonal due to thermal loading of composites.

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