Finite element analysis of Al 2024/Cu-Al-Ni shape memory alloy composites with defects/cracks

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Abstract. In this work, a numerical approach to predict the stress field behaviour of defect/crack in shape memory alloy (SMA) particles reinforced composite known as the adaptive composite is presented. Simulation is based on the finite element method. The critical stress field approach was used to determine the stresses around defect/crack. Thereby stress amplification issue is being resolved. In this paper, the effect volume % of shape memory alloy and shape memory effect of reinforcement for as-cast and SME trained composites are examined and discussed. Shape memory effect known as training is achieved by pre-straining of reinforcement particles by equivalent changes in their expansion coefficients.

1. Introduction
Particulates reinforced composites are of importance for aerospace and automobile applications where the strength-stiffness-weight ratios are decisive factors. There has been substantial research on the failure mechanisms of these materials in order to optimize their design and application. Though primarily more attention was paid to experimental and diagnostic studies [1], the effort has shifted towards computational methods enabled by the refined modeling techniques and declining cost of computational hardware [2]. The failure process in composites is often instigated at micro-sized flaws, which may grow to macro-sized cracks leading to cataclysmic failure. The impairment proliferation hinges on multiple bounds such as the volume fraction of particles, particle strength, interface bonding strength, pre-existing cracks, the contour of the constituent part and their sites inside the matrix. In broad-spectrum, a fracture in particulate composites comprises a combination of matrix failure, particle fracture, and boundary de-cohesion. It is testified that the leading crack may stay absolutely inside the matrix [3]. Even though the elementary mechanical properties of particle-reinforced metal matrix composites (MMC) are loftier to alloys [4], it is habitually set up that their fracture toughness is lesser than that of the monolithic metal alloys [5,6] strengthening mechanisms for proportionally traced cracks with respect to the particle were analyzed by Atkinson [7] who indicated the presence of 1/r singular stress areas for the crack tip very near to the insertion but not in straight collaboration. Intensification in fracture toughness due to crack path deviance around a secondary stage (inclusion) is

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explained by Faber et al. [8] by a numerical model. There are copious computational procedures, described in the literature for modeling crack spread in the presence of particle reinforcements. To study the fracture difficulties the finite element method [9,10] and the boundary element method [11,12] have been extensively engaged. The importances of adaptive composites have been suitably analyzed. The present paper is therefore been concentrated on finite element analysis of as-cast and SME trained composites with aluminium 2024 as a matrix and Cu-Al-Ni shape memory particulates as reinforcement.

2. Prestraining or shape memory effect training of Al 2024/Cu-Al-Ni SMA composite by FEA

The collaboration between reinforced shape memory alloy and the matrix material is perilous subsequently utmost practices necessitate the transmission of strain from the particles to the matrix. Further, the matrix material may ensure an obvious effect on the local state of stress and accordingly, the phase change behaviour of reinforced particles. The present analysis is focused on experimentations of Jonnalagadda et al [13] who measured the stress dispersion in the course of the SMA conversion using the technique of photoelasticity. The analysis first convoluted the creation of the 2D typical model using ANSYS by defining surfaces called patches and hyper patches. The geometry of 1000 μm X 1000 μm of plane stress with a thickness of 100 μm test coupons were considered. After geometric domain, adaptive meshing capabilities were used. Than displacement, force and temperature boundary conditions applied were depicted in the maximum displacement contours. The two types of material used are Al 2024 matrix and Cu-Al-Ni reinforcement with their properties indicated in Table 1.

| Properties of material | Al 2024 | Cu-Al-Ni |
|------------------------|---------|----------|
| Young’s Modulus (GPa)  | 73.1    | 85       |
| Poisson’s ratio        | 0.3     | 0.3      |
| CTE (μm/m °C)          | 24.7    | 17       |

The FEA simulation comprised a sequence of structural and thermal analyses by ANSYS. PLANE 182 elements were selected for structural and thermal analysis. The furthermore problematic portion of the structural investigation was the introduction of prestrain into the ANSYS software.

![Figure 1: Stress-strain graph for pre-straining.](image)

Figure 1 depicts a prestrained stress-strain curve, incorporates a preliminary use of stress in martensitic stage at room temperature which suppresses the yield strength, after reprieve of stress some amount of strain is recuperated but the plastic strain ε_p = 0.01, relics as it is. From Figure 1, seen that ANSYS was not proficient of integrating early strain settings thus equation of total strain becomes.
\[ \varepsilon_{\text{TOT}} = \varepsilon_{\text{ANSYS}} + \varepsilon_0 \]  
\[ \sigma = E \varepsilon_{\text{ANSYS}} + \varepsilon_0 \]  

The total stress is given by,

It is assumed that primary stress is equal to zero, therefore above equation is interpolated for \( \varepsilon_{\text{ANSYS}} \) over the phases and yields,

\[ \varepsilon_{\text{ANSYS}} = \left( \frac{\sigma - \varepsilon_{\text{Aust}} \sigma}{\varepsilon_{\text{MAT}} \sigma} \right) \varepsilon(T-67) \]  

An equation produces equivalent negative expansion means shrinkage and the expansion coefficient agrees to the transformation effect from 67 to 87 °C.

Therefore, \( \alpha_x = \varepsilon + 17 \times 10^{-6} \) now, the CTE \( \alpha \) includes the prestraining and marks the composite model as anisotropic.

3. FEA simulation of stress field behaviour of the as-cast and SME trained Al 2024/Cu-Al-Ni composites

In ANSYS post processing stress field behavior is predicted based on Tresca-failure criteria. The stresses of as-cast and SME trained composites for different vol. % from 0 to 15 % in steps of 5%. The two defects/cracks were created in a test coupon at a distance of 200 to 300 and 700 to 800 microns in the x-axis known as ‘crack plane’. In this, the composites are trained by incorporating the prestraining method.

**Figure 2:** Variation of normal stress in the x-direction (crack plane) of as-cast and SME trained composites for 0% Cu-Al-Ni SMA volume fraction.

**Figure 3:** Variation of normal stress in the y-direction of as-cast and SME trained composites for 0% Cu-Al-Ni SMA volume fraction.
Figure 4: Variation of shear stress in xy-direction of as-cast and SME trained composites for 0% Cu-Al-Ni SMA volume fraction.

Figure 5: Variation of normal stress in the x-direction (crack plane) of as-cast and SME trained composites for 5% Cu-Al-Ni SMA volume fraction.

Figure 6: Variation of normal stress in the y-direction of as-cast and SME trained composites for 5% Cu-Al-Ni SMA volume fraction.

Figure 7: Variation of normal stress in xy-direction of as-cast and SME trained composites for 5% Cu-Al-Ni SMA volume fraction.

Figure 8: Variation of normal stress in the x-direction (crack plane) of as-cast and SME trained composites for 10% Cu-Al-Ni SMA volume fraction.

Figure 9: Variation of normal stress in the y-direction of as-cast and SME trained composites for 10% Cu-Al-Ni SMA volume fraction.
Figure 10: Variation of normal stress in xy-direction of as-cast and SME trained composites for 10% Cu-Al-Ni SMA volume fraction.

Figure 11: Variation of normal stress in the x-direction (crack plane) of as-cast and SME trained composites for 15% Cu-Al-Ni SMA volume fraction.

Figure 12: Variation of normal stress in y-direction of as-cast and SME trained composites for 15% Cu-Al-Ni SMA volume fraction.

Figure 13: Variation of normal stress in xy-direction of as-cast and SME trained composites for 15% Cu-Al-Ni SMA volume fraction.

Figure 2 to Figure 4 show normal and shear stress variations for as-cast and SME trained composites at 0% volume fraction. It is seen from the graph that, maximum fluctuation of stresses of both as-cast and SME trained composites takes place at the regions of the cracks. Also, the stress values of SME trained composite follows the same path as of the as-cast composite. Figure 5 to Figure 7 shows the stress variations for 5% volume fraction composite. It is perceived from the graph that, stress values of as-cast composite shows slight upper surge at a distance between 400 to 600 microns. While at the places of cracks it behaves as 5% SMA volume fraction composite. In, 10 % volume fraction, SME trained composite, stress along x-direction follows upper shift as compared to as-cast composite. Whereas, for both the composites stresses in y and xy-direction almost overlaps with one another as shown in Figure 8 to Figure 10.Finally, for 15 % SMA volume fraction, stresses of as-cast composite shows maximum fluctuations at the places of cracks and SME trained composite exhibits almost zero level of stresses along the crack plane. Overall SME trained composites show remarkable changes in the stress values in x, y, and xy-direction for 15 % SMA volume fraction. This is due to shape memory property commence within the 15% SMA particulates vol. % subjected to heating known as training or prestraining.
Figure 14: Sx-Normal stress contour of as-cast composite for 15% volume fraction along the x-direction.

Figure 15: Sy-Normal stress contour of as-cast composite for 15% volume fraction along the y-direction.

Figure 16: Sxy- Shear stress contour of as-cast composite for 15% volume fraction along xy-direction.

Figure 17: Sx- Normal stress contour of SME trained composite for 15% volume fraction along the x-direction.

Figure 18: Normal stress contour of SME trained composite for 15% volume fraction along the y-direction.

Figure 19: Shear stress contour of SME trained composite for 15% volume fraction along the xy-direction.
Further, for the substantiation of above results, the stress contours of as-cast and SME trained composites are described in the Figure 14 to Figure 19. It is seen from the contours that, maximum stress was found at the matrix-reinforcement interface. Consequently, shear stress contours of as-cast and SME trained composites were completely mirrored. The maximum stress values of as-cast and SME trained coupons for 15 % volume fraction along three directions are 46.6, 45.5 and 18.5 MPa and 1.5, 2.0 and 0.9 MPa respectively. It clearly indicates from the results that stress values drastically drops for SME trained composites; it is due to the fact that, shape memory property is the main cause to reduce stress values i.e. oscillatory nature of stresses along the crack plane. In general, it has been seen that oscillatory nature of stresses of as-cast composites compares well with the SME trained composites data, but the stress values of SME trained composites were much lower as compared to as-cast composites. This could be ascribed that the as-cast composites are sensitive to defects/cracks, whereas in the SME trained composites, prestraining or shape memory effect has lowered the oscillatory nature of stresses at the places defects/cracks in the crack plane.

4. Conclusions
The method of engaging a variable expansion coefficient to simulate an effect of prestrain in Al2024/Cu-Al-Ni SMA composites have been applied successfully using ANSYS. The investigation involved SME in composites and demonstrated defects/cracks behavior by the prediction of reduced stress values of SME, trained composites. Shape memory in SMA composites produces lower stress values along the crack plane, which means that these composites possess almost zero stresses at the place of defects by reducing the oscillatory nature of stresses. In the view of this, the composites have been utilized in the applications of force or deflection actuators.

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