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Finite Element Simulation and Experimental Investigation of Al 2024/Cu-Al-Ni Shape Memory Alloy Composites

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Abstract: This encompasses finite element simulation and experimental investigations of the shape memory effect due to the presence of Cu-Al-Ni SMA particulate reinforcement in Al alloy matrix known as SMA composites. Simulation was accomplished using ANSYS where the prestrain was modeled by equivalent alterations in the expansion coefficient of the SMA particulates. The properties namely young's modulus, poisson's ratio and coefficient of thermal expansions were simulated and their predictions were compared with experimental data for as-cast and SME trained composites at different temperature loads known as 'training'. An FEA and experimental investigation SMA composites properties allows assessment of the effect SMA volume fraction and shape memory effect at different temperatures. These outcomes shack light on the design of SMA reinforced composites.

Key words: Al (2024), ANSYS, Cu-Al-Ni, finite element simulation, shape memory effect, temperature

INTRODUCTION

Efforts into SMA composites were started in the late 1980's when (Rogers and Robertshaw, 1988) first embedded NiTiNOL wires in a laminated polymer matrix composite. Particulate reinforced composites are important for aerospace and automobile applications where the strength-stiffness-weight ratios are decisive factors. An exciting behavior of SMA composites has been increasingly investigated for application in roles such as actuators (Benafan *et al*., 2014), couplers and vibration dampeners (Casciati *et al*., 2008) in the aerospace (Calkins and Mabe, 2010), civil (Dong *et al*., 2010), petroleum industries (Anderson *et al*., 1999) as well as in MEMS devices (Bellouard, 2008). Shape memory composites can be used keenly to regulate internal stress state elastic modulus in the case of hard matrices and shape change in the case of soft matrices (Balta *et al*., 1999; Friend and Morgan, 1995). Alloys of shape memory have received great attention for their unique thermomechanical actions such as Shape Memory Effect (SME) and pseudoelastic effect. The shape memory effect was used to expand properties in SMA/metal matrix composites due to the internal forces related with thermal regaining as initially proposed by Yamada *et al*. (1993). Al 2024 was used as matrix due to upright machining features, upper strength and fatigue confrontation than both 2014 and 2017. Cu-Al-Ni shape memory alloy is used as reinforcement because Cu-Al-Ni SMAs are the most striking for real applications due to their low cost and better shape memory effect. In this view, SMAs are excellent candidate reinforcements for this purpose.

By incorporating SMAs into aluminum alloys, fiber or particle, SMAs-reinforced aluminum matrix composites (SMAs/Al) with special functions can be produced (Armstrong and Kino, 1995). During the past decades, much research has been focused on this respect. SMAs/Al composites are opened a new vista for further research in MMCs in a quest to meet the going demands of technologies which require tailor-made materials. The present simulation and experimental investigations have been carried out to investigate the properties such as Young's modulus, poisson's ratio and CTE of Al 2024/Cu-Al-Ni SMA composite for the effect SMA volume fraction and SME training at different temperatures.

MATERIALS AND METHODS

Mechanism of shape memory effect by finite element simulation: The prestraining mechanism is incorporated for shape memory effect in finite element simulation of

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Table 1: Material properties of Al 2024 and Cu-Al-Ni

Material properties	Al 2024	Cu-Al-Ni
Young's modulus (GPa)	73.1	85
Poisson's ratio	033	0.3
CTE (μm/m°C)	24.7	17

SMA composite is described as follows. An analysis was made using ANSYS where the prestrain was modeled by corresponding changes in the expansion coefficient of the reinforced SMA particulates. Simulations consist of a series of structural/thermal analysis. The geometry of composite test coupon considered was 1000×1000 μm, 2-dimensional PLANE 182 element plane stress with thickness of 100 μm was considered for the analysis. The Al 2024 matrix and Cu-Al-Ni SMA reinforcement properties considered in the analysis are given in Table 1.

The maximum challenging part of the analysis was to consequence into the ANSYS Software the pre-strain that the particulates had. To include primary strain conditions it is assumed that the primary stress is equal to nothing and equation is interpolated for ε_{ANSYS} between Martensite and Austenite phases, it produces:

$$\varepsilon_{ANSYS} = \left(\left(\sigma\text{-}\left(E_{Aust}\ \varepsilon_{o}\right)/E_{Aust}\text{-}\sigma/E_{Mart}\right)\times\left(T\text{-}67\right)\right)/\left(87\text{-}67\right) \quad (1)$$

Equation 1 yields corresponding expansion coefficients, negative as it really represents shrinkage which is related to the shape memory effect between 67-87°C:

$$\alpha_{X} = \varepsilon{+}17\times10^{T}\left(\text{-}6\right) \quad (2)$$

Thermal expansion coefficient, α now includes the pre-straining effect, effectively makes α anisotropic, depending on the direction of pre-strain.

RESULTS AND DISCUSSION

Finite element simulation and experimental investigation of AS-cast and SME trained composites: FEA simulation and experimental investigation results of Al 2024/Cu-Al-Ni SMA composites allows assessment of the effect SMA volume fraction and shape memory effect at various temperature loads. A family of curves has been generated based on simulation and experimental results which provides the results of properties such as Young's modulus, Poisson's ratio and CTE of SMA composites.

Young's modulus and Poisson's ratio: A structural/thermal analysis (in sequential form) was applied to the as-cast and SME trained composites. The temperature was raised from 50-100°C in 10°C steps and

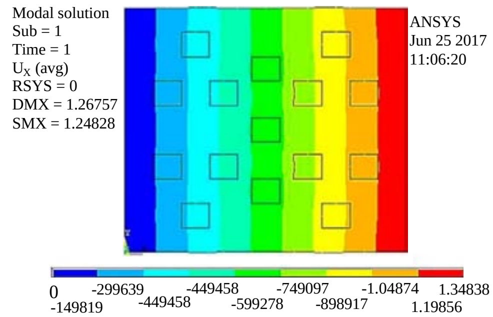

Fig. 1: U_x displacement contour of as-cast composite for 15% SMA volume fraction

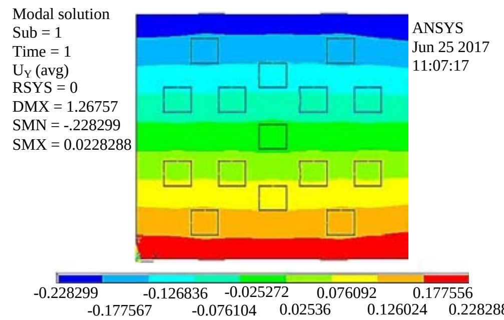

Fig. 2: U_y displacement contour of as-cast composite for 15% SMA volume fraction

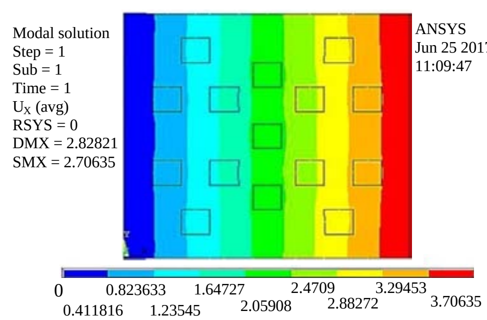

Fig. 3: U_x displacement contour of SME trained composite for 15% SMA volume fraction at 100°C

SMA volume fraction increased from 0-15% in 5% steps. Predictions were needed at 50, 60, 70, 80, 90 and 100°C for 0-15% SMA volume fractions to compare with the experimental data and hence the appropriate predictions were made by linear interpolation techniques between the closest corresponding steps.

Figure 1-4 show the displacements in the x and y directions as predicted by ANSYS for 15% SMA volume fraction of as-cast and SME trained at 100°C composite test coupons which shows the maximum displacements

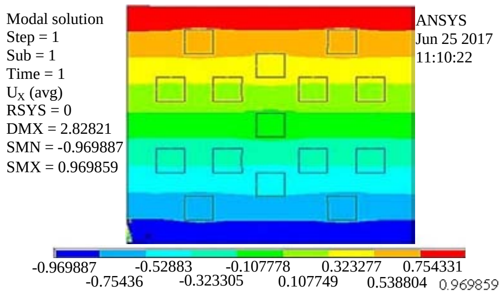

Fig. 4: U_y displacement contour of SME trained composite for 15% SMA volume fraction at 100°C

U_x = 1.348 and U_y = 0.228 for as-cast, U_x = 3.706 and U_y = 0.969 for SME trained composite test coupons which indicates the increasing trend of displacements in both x and y axis as the composite was trained for shape memory effect at temperature of 100°C. From these displacement values, equivalent Young's modulus and poisson's ratio values are calculated using the following equations: strain in X-direction:

$$\varepsilon_x = U_x/1000 \tag{3}$$

Strain in Y-direction:

$$\varepsilon_y = U_y/1000 \tag{4}$$

Young's modulus:

$$E = \sigma_x/\sigma_y \tag{5}$$

Poisson's ratio:

$$v = \frac{\varepsilon_x}{\varepsilon_y(6)} \tag{6}$$

Figure 5 and 6 show a plot of Young's modulus and Poisson's ratio as a function of SMA volume fraction and SME training temperature in the structural analysis by ANSYS. As the Al 2024/Cu-Al-Ni composite was heated, its matrix expands which affects mainly the Cu-Al-Ni particulates and causes strengthening of the composite. The predicted values of Young's modulus increase and Poisson's ratio decrease almost linearly up to 5% SMA volume fraction. Thereafter, Young's modulus decreases slightly up to 10% and increases slightly up to 15% of SMA volume fraction. Similarly, Poisson's ratio increases slightly up to 10% and decreases up to 15% of SMA volume fraction. The experimental data follow the same trend where there was a predicted Young's modulus and Poisson's ratio values of as-cast composites were 77.3 and 0.258 GPa, respectively for 5% SMA volume fraction against an experimental values of 76.5 and 0.267 GPa, respectively.

Whereas, for SME trained composites were 89.3 and 0.02 GPa, respectively for 5% SMA volume fraction at 100°C against an experimental values of 90.01 and 0.028 GPa, respectively which were very close to the prophecies within the estimated experimental errors.

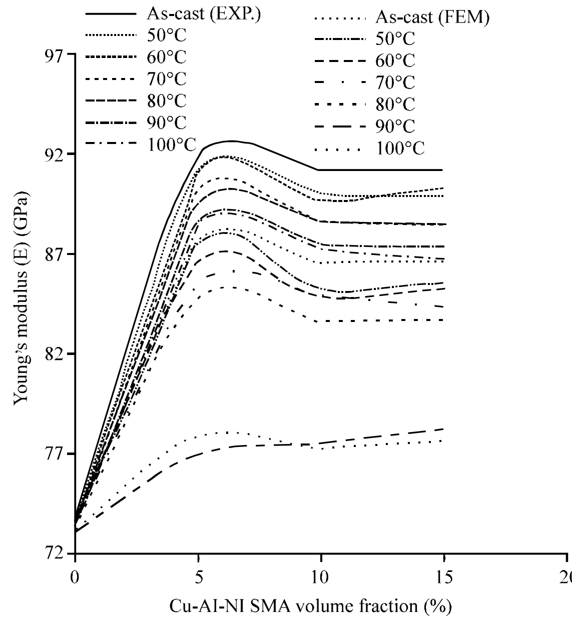

Fig. 5: Variation of Young's modulus with SMA volume fraction for as-cast and SME trained composites both in FEM and experimental method (Al 2024+0, 5, 10 and 15%, Cu-Al-NI SMA)

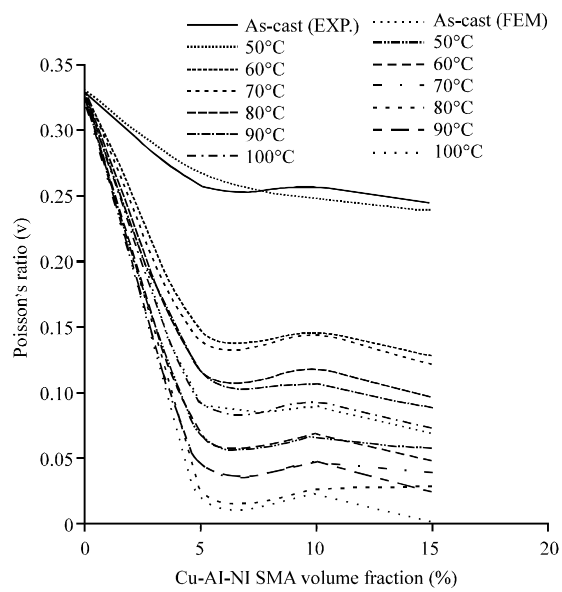

Fig. 6: Variation of Poisson's ratio with SMA volume fraction for as-cast and SME trained composites both in FEM and experimental method (Al 2024+0, 5, 10 and 15%, Cu-Al-NI SMA)

Coefficient of Thermal Expansion (CTE): A thermal/structural analysis in sequential form was applied to the as-cast and SME trained composites. The temperature was raised from 110-120°C in 5°C steps and SMA volume fraction increased from 0-15% in steps of 5%. Predictions were needed at 110, 115 and 112°C for 0-15% SMA volume fractions to comparewith the experimental data at these temperatures and volume fractions and hence the appropriate predictions were estimated by linear interpolation between the closest corresponding steps.

Figure 7-10 show the displacement in the x-direction as predicted by ANSYS for 15% SMA volume fraction of as-cast and SME trained at 110, 115 and 120°C composite test coupons which shows the maximum displacement $U_x = 2.425$ for as-cast and $U_x = 2.667$, 2.788 and 2.910 at 110, 115 and 120°C, respectively for SME trained composites which shows an increasing trend of displacement as the composite was trained for shape memory effect between 100 and 120°C. From these displacement values, equivalent CTE values are calculated using Eq. 7:

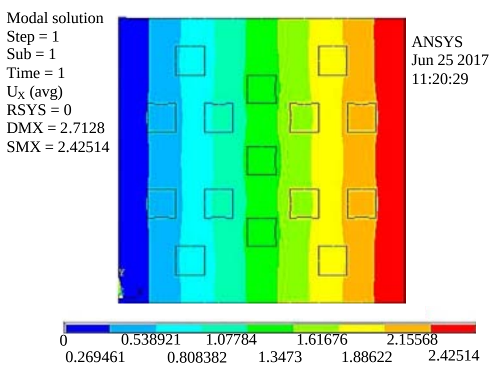

Fig. 7: U_x displacement contour of as-cast composites test coupons for 15% volume fraction

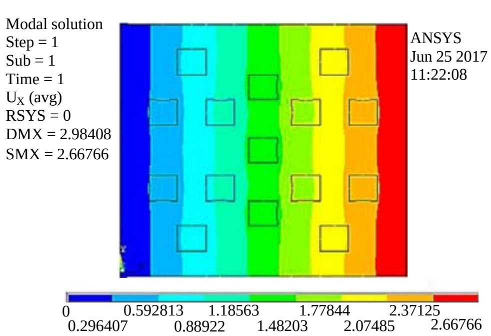

Fig. 8: U_x displacement contour of SME trained composite test coupons at 110°C for 15% volume fraction

$$\alpha = U_x / \left(\left[1000 X_{\text{riseintemperature}} \left(100°C \right) \right] \right) \quad (7)$$

Figure 11 illustrates a plot of CTE as a function of SMA volume fraction and SME training temperature in the structural analysis by ANSYS. As the Al 2024/Cu-Al-Ni composite is heated, its matrix expands which affects mainly the Cu-Al-Ni particulates and causes increase in its thermal expansion.

The predicted value of CTE decreases almost linearly throughout the SMA volume fraction. While increases as the SME training temperature increases. The experimental data follow the same trend where there is a predicted CTE value of as-cast composite is 24.25 μm/m°C against an experimental value of 24.21 μm/m°C. Whereas for SME trained composites 26.67, 27.88 and 29.1 μm/m °C against an experimental values of 25.76, 26.97 and 28.17 μm/m°C at 110, 115 and 120°C, respectively for 15% SMA volume fraction. It is observed from the results that the SMA particulates continue shrinking in their shape memory recovery stage as the specimen is trained further and as a result they completely balance the matrix expansion effect.

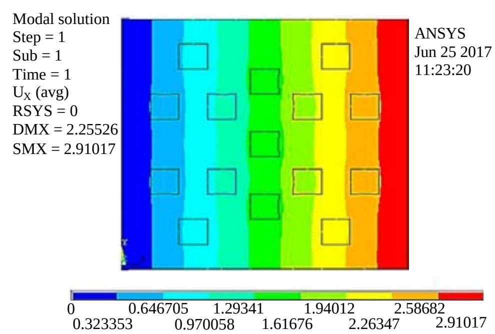

Fig. 9: U_x displacement contour of SME trained composite test coupons at 115°C for 15% volume fraction

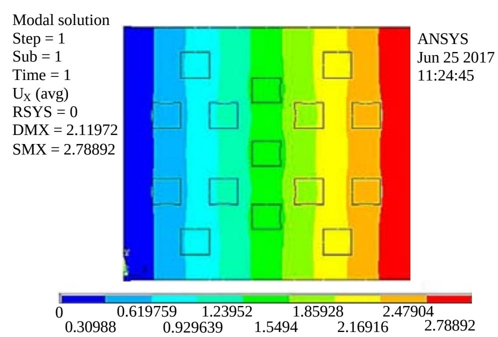

Fig. 10: U_x displacement contour of SME trained composite test coupons at 120°C for 15% volume fraction

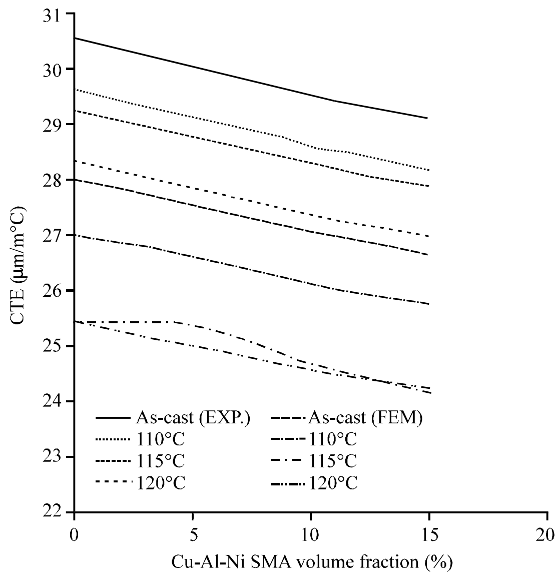

Fig. 11: Variation of CTE with SMA volume fraction for as-cast and SME trained composites at 110, 115, 120°C for both FEM and experimental method (Al 2024+0, 5, 10 and 15%, Cu-Al-NI SMA)

CONCLUSION

The following conclusions have been drawn with respect to the results of finite element simulation and experimental investigations of properties of the Al 2024/Cu-Al-Ni composites. The technique of employing a varying expansion coefficient to simulate the effects of prestrain in SMA particulates has been applied successfully. The Young's modulus of SME trained composite increases more as compared to as-cast composite in the volume fraction between 5-10%. The Poisson's ratio of SME trained composite decreases less as compared to as-cast composite in the volume fraction between 5-10%. The CTE of as-cast composite decreases as the SMA volume fraction increases. Whereas CTE of SME trained composite increases as the SME training temperature is increased. Overall, shape memory effect takes place in the composites between 5 and 10% Cu-Al-Ni volume fraction within the temperature of 120°C.

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