Thermal Mismatch Stresses in a Metal Matrix Composite - A Finite Element Analysis

K. Prahlada Rao, D. P Girish, M. Krishna, Madhu. B. V

Abstract: ***The coefficients of thermal expansion (CTEs) of aluminum and aluminum/Al_2O_3 metal matrix composites (MMCs) are measured using a dilatometer and analysis of residual thermal stresses by Finite Element Analysis (FEA). The MMCs were prepared by liquid metallurgy technique for varying percentages of reinforcement in steps of 0, 5, 10, and 15% by weight. The CTE is expected to vary with relative residual strains which in turn are dependent on the percentage of reinforcement when cooled from 500°C to room temperature. The experimental CTE values were compared with developed model. FEA has been used to investigate the distribution of residual thermal stresses in the interfacial region. The result indicates that the properties of the interfacial region affect the stress distribution.***

Index Terms**: *Al 6061, CTE, FEA, Liquid Metallurgy, TMA.***

I. Introduction

Metal matrix composites (MMCs) have enhanced properties including higher strength, lower thermal expansion, higher fatigue life, and higher wear properties, as compared to those of their matrix alloys [1]. Al MMCs find potential application in several thermal environments, especially in automobile engine parts, space applications, such as drive shafts, cylinders, pistons, and brake rotors [2]. An investigation relating to the temperature profiles of the piston area in a diesel and petrol engine has shown that the temperature can reach as high as 400°C in certain regions of the piston [3]. As the piston and cylinder areas are exposed to high temperature, the materials used should have sufficient stability. Al MMC reinforced with ceramic particulates have high specific strengths modulus at room and elevated temperature and also have excellent wear resistance [3], high thermal conductivity [4], low thermal expansion [5], and good dimensional stability [6]. For these reasons metal-ceramic particulate composites are used extensively as electrical contacts, cutting tools, rocket nozzles, spark-plug electrodes, bearing, pistons etc [7]. But when the fabrication of a MMC involves its cooling from a high temperature stress-free state, plastic-elastic residual deformation fields can be generated within and around the particles due to the differential thermal expansion between the particles are spherical of equal radius and randomly distributed in the matrix [3].

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Few studies [4]-[6] have been focused on thermal mismatch of MMCs, Skirl et al. [8], have examined the effect of other material parameters, such as elastic properties of matrix and reinforcement, size and shape of the reinforcement on the CTE and, internal residual strain of Al_2O_3 reinforced aluminum MMCs. Balch et al. [9] reported variation of thermal strain with respect to temperature for Al_2O_3 reinforced with aluminum MMCs, where they have attempted to compare the experimental and analytical results obtained. They were found to be reasonably in good agreement for thermal cycle with temperature difference.

II. Theoretical Model for CTE of Particle Reinforced MMC

In this study the matrix is considered to yield under the condition of a constant yield stress, and the yielding is considered independent of the stress axis and the stress and strain associated with a misfitting spherical hard particle in the absence of plastic relaxation i.e. under pure elastic condition. At melting temperature, the radii of the matrix hole and the particle (a) are identical. However upon cooling, the matrix hole tries to contract to (a_m) the ceramic particle, with a lower CTE, tries to contract only to (a_r) as shown in the Fig. 1.

The effective radius of the reinforcement particle under the constraint of the matrix is (a_e). The relation of their radii as following equations:

$$a_m = a\,(1-\alpha_m\,\Delta T) \qquad (1)$$

$$a_p = a\,(1-\alpha_p\,\Delta T) \qquad (2)$$

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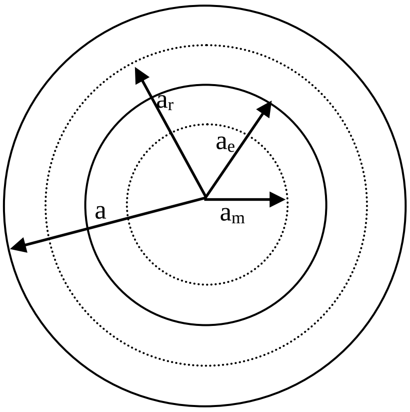

Fig. 1. Schematic of spherical particle and matrix hole.

$$a_e = a_m + \delta_m \quad (3)$$

$$a_e = a_p - \delta_p \quad (4)$$

$$a_m + \delta_m = a_p - \delta_p \quad (5)$$

$$\delta_m + \delta_p = a_p - a_m = a\,\Delta T\,(\alpha_m - \alpha_p) \quad (6)$$

Where αm, CTE of matrix αf, CTE of Reinforcement particle, ΔT is difference temperature, $\Delta\alpha = \alpha_m - \alpha_p$ and δ_m, δ_f and δ are the misfit factor of matrix alloy, reinforcement particle and total respectively.

Where $a \approx a_p$ (size of the ceramic particle) the ceramic particle has low CTE compared to matrix alloy.

$$\delta = a_p\,\Delta T\,\Delta\alpha \quad (7)$$

However the volumetric shrinkage for single particle can be expressed as follows.

$$\Delta v = 4/3\,\pi\,(a_p)^3\,\Delta T\,\Delta\gamma \quad (8)$$

Where $\Delta\beta = \beta_m - \beta_p = 3\,\Delta\alpha$

β_m and β_p are the volumetric CTE of matrix and reinforcement particle.

$$\Delta v = 4/3\,\pi\,(a_p)^3\,\Delta T\,3\,\Delta\alpha$$

(9) In the MMCs 'n' number particles presents, the total volume shrinkage is given by

$$dv = \Delta v_1 + \Delta v_2 + \Delta v_3 + \ldots\ldots\ldots\ldots\ldots + \Delta v_n$$

(10)In this work it is assumed that all particles dimension are uniform. The equation is rewritten as

$$dv = n\,(4/3)\,\pi\,(a_p)^3\,\Delta T\,3\,\Delta\alpha \quad (11)$$

$$\text{whereas } n = \frac{V_p}{(a_p)^3\ 4/3\ \pi} \quad (12)$$

Where V_p is volume of the reinforcement in MMCs. Equation (10) can be rewritten as follows.

$$dv = 3V_f\,\Delta T\Delta\alpha \quad (13)$$

The V_m is volume of the matrix, V_c is volume of the composite, and γ_c is the CTE of the composites. When heating the matrix metal from the room temperature the change of the volume is given by

$$dv_m = \beta_m\,V_m\,\Delta T \quad (14)$$

But in the composite the matrix tries expand but mismatch volume compensate some percentage is given by

$$dv_c = dv_m - dv \quad (15)$$

i.e., $dv_c = \beta_m\,V_m\,\Delta T - 3\,V_f\,\Delta T\,\Delta\alpha$ (16)

$$\beta_c = v_m\,\beta_m - 3\,v_f\ \ \Delta\alpha \quad (17)$$

$\beta_m = 3\ \alpha_m$, v_m and v_f volume fraction of matrix and reinforcement.

$$\beta_c = v_m\,3\,\alpha_m - v_f\,3\Delta\alpha \quad (18)$$

Finally the equation can be modified

$$\alpha_c = v_m\alpha_m - v_f\,\Delta\alpha \quad (19)$$

When the $v_f = 0$ then the $\alpha_c = \alpha_m$ or $v_m = 0$ then the $\alpha_c = \alpha_f$.

The present investigation was undertaken with the main objective of studying the CTE of aluminum MMCs reinforced with Al_2O_3 particles in both theoretical and experimental methods. And also thermal mismatch was studied using FEM embedding a composite sphere, consisting of an inclusion particle surrounded spherical matrix material. The thermal mismatch of the MMCs was measured between 35°C and 500°C by a high-precision thermal mechanical analyzer (TMA). The specific results are presented for the Al/Al_2O_3 MMC that illustrates the development during cooling of this residual field their dependence on the concentration of the Al_2O_3.

III. Experimental Procedure

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A. Material selection

The present study makes use of the liquid metallurgy technique. Al6061, which exhibits excellent casting properties and reasonable strength, was used as the base alloy. This alloy is best suited for mass production of lightweight metal castings. The chemical composition of the Al6061 alloy is given in Table I.

Al_2O_3 is a ceramic material used for high temperature applications because of its high melting point, lower density, and capacity to retain high strength at elevated temperature.

Table I. Chemical composition of Al6061 alloy

CHEMICAL COMPOSITION OF ALUMINIUM 6061 ALLOY	
Mg	0.92
Si	0.76
Fe	0.28
Cu	0.22
Ti	0.10
Cr	0.07
Zn	0.06
Mn	0.04
Be	0.003
V	0.01
Al	Bal.

B. Specimen preparation

Specimens for CTE tests were prepared using compocasting technique, with variation of the Al_2O_3 reinforcement in steps of 5, 10, and, 15% by weight, based on the technique described by Sharma et al. [10]. Specimens for CTE testing 10 mm x 5 mm x 2 mm in size machined from the prepared MMCs. Specimen surfaces were polished with 1μm diamond paste. Four samples of each composite were tested under same condition to verify the reproducibility of the data.

C. Thermal Mechanical Analyzer (TMA) Test

CTE measurements were performed from room 35°C to 500°C for the heating part of the cycle and from 500 °C to room temperature (35 °C) for the cooling part of the cycle using a standard commercially available TMA (Model Number TMA-50, Shimadzu, Japan) at sweep rate of 5°C/min. The specimen was positioned on a quartz fixture and a standard expansion probe was placed on the specimen to measure changes in length. The whole experiment was carried out in a furnace whose temperature could be controlled and monitored. The dimensional changes occurring as a function of temperature was monitored by a linear variable differential transformer (LVDT) attached to the probe. A thermocouple adjacent to the specimen recorded the temperatures change. Both the LVDT and the thermocouple were interfaced with a computer. No liquid phase transformation was observed for the selected temperature range in the Al6061/Al_2O_3 MMCs tested. The data were collected in terms of percent linear change (PLC) with respect to temperature. The PLC curve for each specimen was plotted through one complete cycle of heating followed by cooling.

D. Residual stress analysis

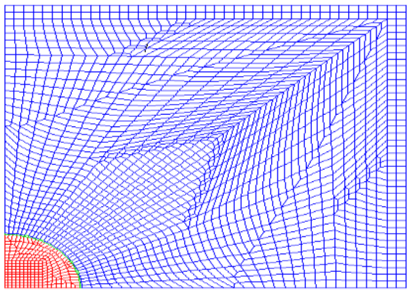
For matrices containing a particulate as second phase, upon cooling from the processing temperature, residual stresses would have developed due to the difference in the thermal expansion and elastic properties of the matrix and the particulate [10]. The thermal expansion of Al6061 alloy is much greater than that of the Al_2O_3. A quantitative analysis of residual stress resulting from the thermal mismatch in Al_2O_3-reinforced composite was determined by FEA method.

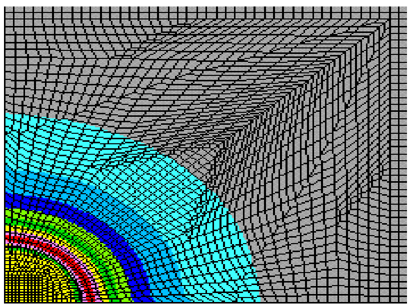
E. Description of the finite element model

FEA of MMCs was implemented using the NISA386 (EMRCNISA). The particulate and matrix were described using 2-D four-node iso-parameter element, while the interfacial region was treated as a thin layer with a finite thickness and independent properties and was simulated using 2-D four-node concrete solids. The inclusion (reinforcement) behaves elastically and its stiffness is much higher than that of the matrix, so that the reinforcement can be regarded as being rigid.

In present work, 2D self-consistent embedded cell models with random particle arrangements. Fig. 2 describes schematically a typical plane strain (2D) embedded cell model with a volume fraction of f = (d / D)2, where instead of using fixed boundary conditions around the particle-matrix an equivalent composite material with the thermo-mechanical behavior to be determined iteratively in a self-consistent manner.

Typical FEA mesh and for corresponding boundary conditions are given in Fig. 2(b), where a spherical particle is surrounded by a spherical shaped metal matrix, which is again embedded in the composite material for which the thermo-mechanical behavior is to be determined.





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(b)

Fig. 2. The finite element mesh used for the calculation of the effect of volume fraction of reinforcement on the residual stresses at the interface **(a)** before and **(b)** after thermal load.

F. Iterative modeling procedure

The boundary conditions were set in such a way that the compatibility of the unit cell with contiguous cells of the square array in the infinite composites could be satisfied. The nodes on the bottom face of the model were not allowed to move in the y-direction, while the nodes on the top face of the model were coupled together to shift an equal amount of displacement in the y-direction. Similarly, the nodes on the front face of the model were not allowed to move in the x-direction, while the nodes on back face of the model were coupled in the x-direction. The displacement at each of the two xy-planes was coupled in the z-direction. Finally, the node at the origin of the model was not allowed to move in any direction to prevent rigid body displacement.

The zero stress of the composites was assumed to be the melting temperature of the matrix alloy, and the first load applied to the composite was the thermal load imposed during the cooling of the composites. Thermal loads were applied under the assumption that the temperature is spatially uniform throughout the composite. The composites were assumed to

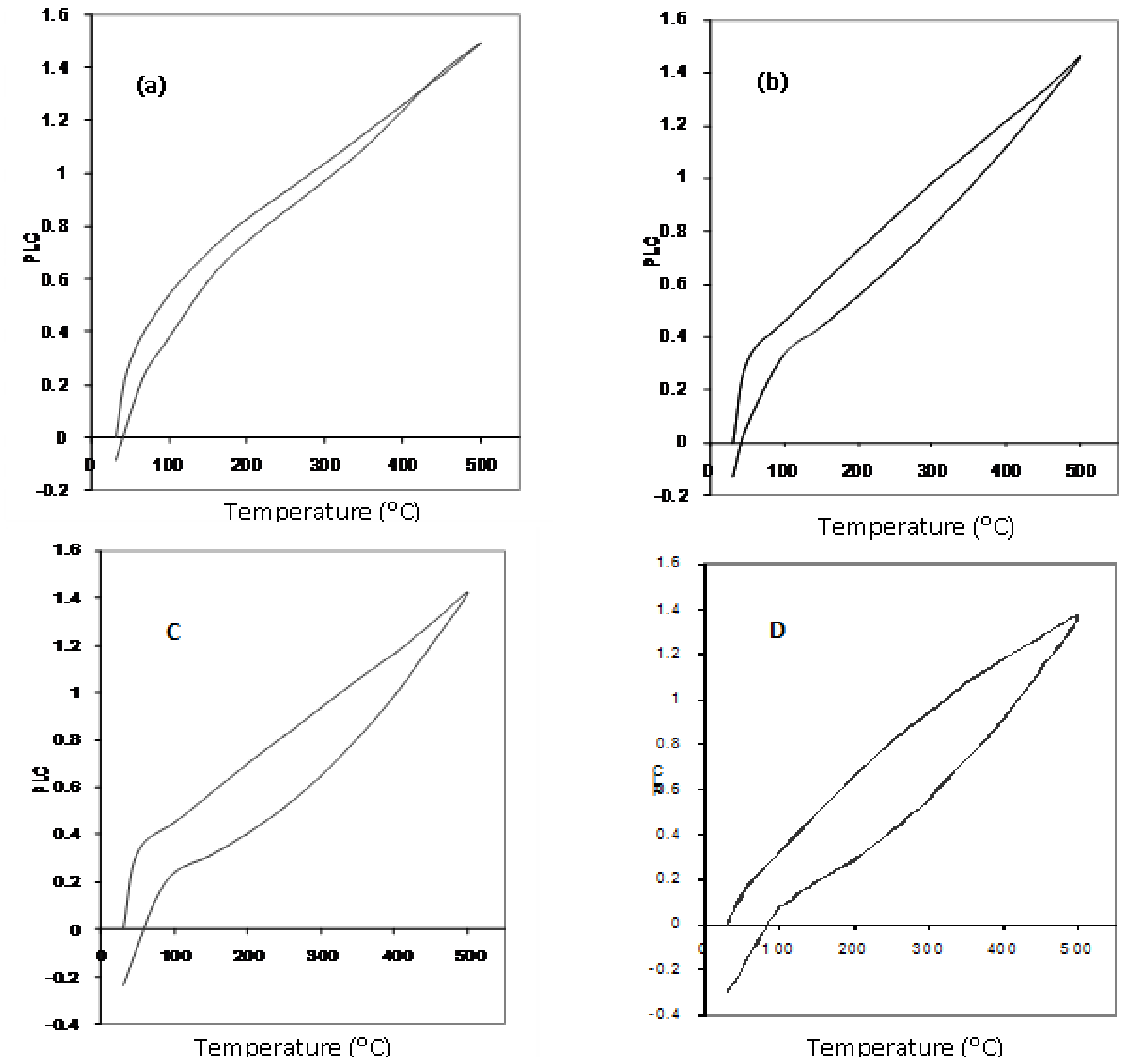

Fig. 3. Variation of the percent linear change as function of the temperature for the 6061Al/Al_2O_3 composites of **(a)** 0%, **(b)** 5%, **(c)** 10% and **(d)** 15 % reinforced. (δ-Hysteresis strain)

cool suddenly from melting temperature to room temperature. Therefore, no time-dependent stress relaxation during cooling was considered. After the cooling event, the residual thermal stresses were estimated using FEA.

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I. RESULTS AND DISCUSSION

A. Percentage linear change (PLC)

The experimental results of PLC of Al_2O_3 reinforced composite with different weight percentages as functions of temperature are shown in the Fig. 3. The Fig. shows that PLC versus temperature curve of different weight percentage reinforced composites had similar characteristics. But the increase in weight percentage of the reinforcement showed a relatively larger contraction. On cooling to room temperature the particulate composites exhibited higher residual strain. That is on successive heating and cooling between room temperature and 500 °C showed significant weak hysteresis strain between the heating and cooling curves at room temperature as shown in the Fig. 3. This is due to sudden cooling of matrix alloy and Al_2O_3 particulate, which is responsible for a major portion of the residual contraction obtained in these composites upon cooling.

Thermal behavior for all cycles was very similar. Curves representing typical thermal strain for heating and cooling are shown in the Fig. for matrix alloy and MMCs. In contrast, a clear hysteresis between heating and cooling occurs for the composites in the initial section of heating are higher than that of matrix alloy. In previous work [6], it was reported that the particulate used in the composite containing Al_2O_3 is larger than those used in the unreinforced Al6061 matrix alloy. Hoffman et al. [11] have believed that the hysteresis of both the thermal strain and CTE data is caused by visco-plastic deformation in the metal phase. This deformation occurs by yielding followed by cavitations, and also by time dependent creep mechanism.

B. CTE results

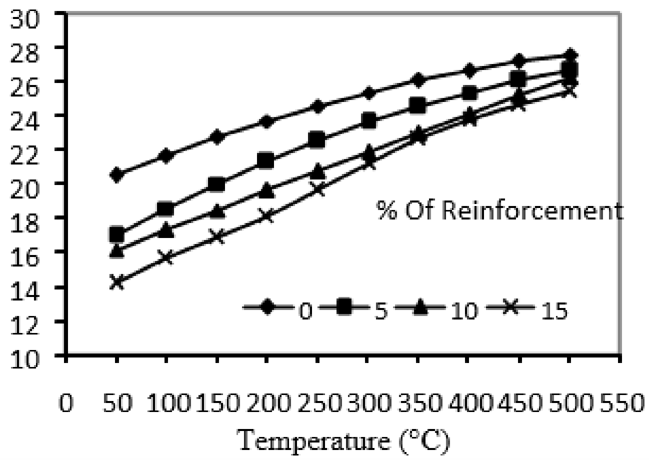

Fig. 4. CTE versus temperature for the given composites

One observes a drastic reduction in the CTE of the composite in comparison with that of the matrix alloy, which indicates that in these composites, there is good interfacial bonding, due to existence of macroscopic strain. The CTE of the base alloy and composites with variation in temperature are shown in the Fig. 4. The CTE of both pure alloy and composite was found to increase with increasing temperature

Xu et al. [12] are of the opinion that the lattice distortion at the interface will affect the CTE value of the composite. Since the interfacial area will depend on the particle size, the CTE of composite will vary with particle size as well as shape. Denath et al. [13] in their paper believe that the increase in the reinforcement of ceramic particulate slightly decreases CTE. The same results were found by Elomari et al. [14].

C. Comparison of experimental results with theoretical calculation

Table II. Comparison of the experimental CTE of the composites with the theoretical model.

Temp. °C	Coefficient of thermal Expansion in K^{-1}					
	5 % Al_2O_3		10 % Al_2O_3		15 % Al_2O_3	
	Exp.	The.	Exp.	The.	Exp.	The.
50	16.97	19.73	16.10	18.96	15.56	18.18
100	18.56	20.84	17.28	20.00	16.66	19.20
150	20.00	21.85	18.46	21.00	17.69	20.13
200	21.33	22.78	19.61	21.80	18.84	21.00
250	22.53	23.63	20.75	22.69	19.64	21.75
300	23.61	24.40	21.88	23.42	21.23	22.45
350	24.56	25.00	23.00	24.00	22.60	23.00
400	25.38	25.69	24.10	24.60	23.76	23.60
450	26.08	26.13	25.18	25.09	24.71	24.10
500	26.66	26.55	26.25	25.49	25.44	24.43

When select the matrix and reinforcement with same CTE and different Elastic modulus, there is no thermal mismatched can be seen meanwhile select the matrix and reinforcement with same Elastic modulus and with different CTE there is thermal mismatched can be observed. That means the thermal mismatch is depends mainly on CTE only.

Experimental results of CTE measurements conducted on the composites are tabulated together with the predicted values obtained from the four expressions given in previous section, in Table II. The measured CTEs of the composite with 0, 5, 10 and, 15% weight of Al_2O_3 reinforcement Al6061 agree fairly well with developed model. It could be due to, the anisotropic nature of Al_2O_3 with different coefficient of expansion in different crystallographic direction and the lack of perfect bonding between the metal matrix and Al_2O_3 particulate.

D. Residual thermal stresses

The nature and magnitude of the residual stresses generated in the Al/ceramic particles depend on the mismatch in the CTE between particle and aluminum matrix, as well as on the elastic modulus and Poisson's ratio of the particle and matrix. The mismatch in the elastic/plastic and thermal expansion characteristics of the particles and matrix leads to inhomogeneous plastic yielding during thermal loading, with yield initiating at stresses which are lower than that required in the matrix alloy alone. At higher strains the mismatch results in the development of large stresses within the particles.

The x-direction stresses and the effective (Von Misses) stress in the matrix for a composite cool down from melting temperature (625°C) to room temperature. The stress and strain distributions in a typical unit cell model (2d) are shown in the Fig. 5, which shows the two kind of stress distribution after the cool-down from the melting temperature i.e. radial stress and hoop stress.

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Radial and hoop stresses act as compressive and tensile forces at interface in between the particle and matrix respectively. As expected, the larger CTE of the matrix as compared to the particles creates a tensile hoop stress and a compressive radial stress in the matrix near the particle-matrix interface. Both the maximum hoop and radial stresses are located in the matrix at the interface. The resultant of these two stresses in the matrix decrease away from the interface. The radial compressive residual stress generated inside the particle during the cooling is depicted as a function of the temperature for different volume fractions of the reinforcement. It has been observed that the hoop stress at the interface acts as a compressive rather than a tensile force.

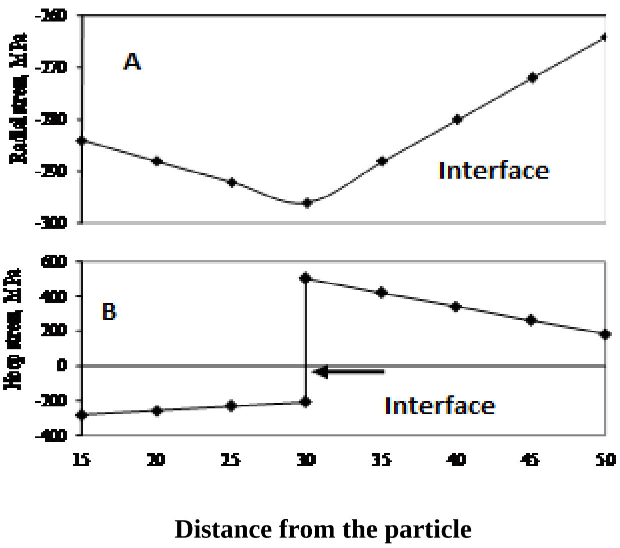

Fig. 5. Residual thermal stresses at the interface for Al_2O_3 reinforced composites **(a)** radial stress and **(b)** the hoop stress

II. CONCLUSION

In this present investigation, the CTE and thermal mismatch residual stresses of MMCs are studied by experimental and FEM techniques respectively, based on this study, the following conclusions were arrived at:

1. Both matrix alloy and composites show a monotonic increase in CTE, with increasing temperature range.
2. The CTE of MMCs decreases with increase in % weight of Al_2O_3 reinforcement.
3. A clear hysteresis is observed in the CTE and strain between heating and cooling is found in both matrix alloy and composites upon thermal cycling.
4. Thermal expansion mismatch leads to residual stress at interface between reinforcement and matrix alloy.
5. Residual thermal stress in the interface depends strongly on the properties of the matrix and reinforcement.
6. The radial thermal stresses in the interface are dominated by the CTE mismatch between the particle and matrix.
7. The CTE mismatch - induces thermo elastic stresses and strain which are highest at the reinforcement particle–matrix interface, and they decrease with increase in distance from the interface.
8. The residual stress in the Al6061/Al_2O_3 MMCs is a result of thermal mismatch which is invariably much greater than their respect matrix alloy.
9. Slow heating and cooling cycles to be relaxed the residual stresses from the MMCs.

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