

## Numerical Study of Residual Thermal Stresses in MMC

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In this paper, numerical study analysis of residual thermal stresses in aluminum matrix reinforced with silicon carbide particles with double- crack has been carried out. is studied in order to determine the thermo-mechanical behavior under the effect of different temperature gradients during cooling. For a more realistic simulation of the microstructure of these materials subjected to different loadings, a representative volume element may be used. In this paper, three different types of crack width  $a = 5 \mu\text{m}$ ,  $10 \mu\text{m}$ ,  $15 \mu\text{m}$ , has been carried. The thermal residual stresses are calculated by considering a wide range of cracks of different penetrations proximity to particle of  $0.1$ ,  $0.2$  and  $0.5 \mu\text{m}$ . regarding the distribution of the stresses along the plane of the crack and in vicinity of the particle, results show that the penetration of the crack in the matrix causes an asymmetry. The inter-distance between crack and particle plays an important role regarding the generation of residual stresses. The lower the inter-distance, the higher the internal stresses of normal residual stresses of  $\sigma_{zz}$ .

*Keywords:* MMC, thermal residual stress, crack.

### 1. Introduction

Nowadays, metal matrix composite materials (MMC) have become important materials in enormous applications, due to their high strength-to-density ratio and excellent wear resistances. During cooling down from manufacturing temperature to room temperature, due to the fact that the constituent materials have different coefficients of thermal expansion, thermal residual stresses are produced, and this affects the mechanical behaviour of MMCs.

The use of composite materials is limited by the lack of efficient tools to predict their degradation and lifetime under service loads, environment and the process induced residual stresses. For a more realistic simulation of the microstructure of these materials subjected to mechanical, thermal or thermo-mechanical loadings, a representative volume element may be used. In the investigations applying FE

method, one common procedure is the numerical generation of a RVE or a unit cell (UC) of the material being studied. A RVE or a UC is a statistical representation of the material [6].

A spherical symmetric model has been employed to calculate thermal residual stresses in Al/SiC particle metal matrix composites [16]. The numerical analysis revealed that residual stresses within the matrix increases when the particulate volume fraction is enhanced. [13] have studied the effects of inclusion shape on residual stresses of MMCs by finite element analysis. Results showed that the use of a cube shaped particle, with sharp corners and edges in the unit cell model, lead to much greater initial hardening behavior than the spherical inclusions and therefore to a greater 0.2% offset yield stress due to stress/strain localization at the particle corners and edges.

[15] In this investigation is to determine the influence of crack penetration in the case  $a = 5 \mu\text{m}$  and for  $d = 0.2, 0.5, 2 \mu\text{m}$  with different temperature gradients to determine the residual thermal stresses and the subsequent mechanical behaviour for the Al-SiC composite.

The numerical investigation of Ye et al [18] which is about the prediction of the crack propagation and the effect of reinforcing particles to the crack propagation behaviour of Al<sub>2</sub>O<sub>3</sub>/Al6061 composite materials has revealed that for the model without reinforcing particles, the stress field near the crack tip is very uniform. The decrease of the stress magnitude away from the crack tip is very gradual. For the model with reinforcing particles, the stress field is not as uniform as it is for the model without reinforcing particles. The disturbance of the stress field is caused by the reinforcing particles, which has different Young's modulus than the matrix material.

The same phenomenon has been previously reported by Ayyar et al. [3, 4]. In addition, it was observed by the authors that less stress concentration exists around the crack tip in the model with reinforcing particles than the model without reinforcing particles, hence, the importance of the use the reinforcing particles to improve fatigue resistance of the materials.

The amount of the normal internal stresses introduced in the matrix and the particle increase with increasing the reheating temperature, a twofold increase in reheating temperature resulted in a twofold increase in equivalent stress as well [5].

The fatigue crack propagation in the MMC bi-material system slows down in the MMC layer side and maximum crack retardation occurs on the boundary of the bi-material system, and Crack in the metal matrix composite layer initiates in the particle-matrix interface and propagates through the base material [8].

In this paper, I present the effect of the penetration of a micro-crack with double-crack (with crack penetration proximity to particle of 0.1, 0.2 and 0.5  $\mu\text{m}$ ) on the thermo-mechanical behavior of a microstructure of a composite of aluminum matrix reinforced with silicon carbide particles subjected to different temperature gradients (cooling process). This was done using the finite element method to numerically predict the residual thermal stresses acting on the microstructure. Only the damage double crack in the aluminum matrix was considered in the present investigation. The simulations were done with Abaqus [1].

## 2. Thermo-mechanical model

In this study I studied thermal residual stress of the MMC, of matrix (Al) and reinforced particles (SiC) was proposed, as shown in Fig. 1 (a). Proposed system was symmetrical, to reduce the calculation; dimensions of the model and mechanical properties of MMC, are presented in Table 1, Table 2.

**Table 1** Dimensions of metal matrix composite [13]

Dimensions of model (MMC)	Length $\mu\text{m}$	Width $\mu\text{m}$	Thickness $\mu\text{m}$	Diameter of particle $\mu\text{m}$
	160	160	80	20

**Table 2** Mechanical properties of Al and SiC used in FEM simulations [3]

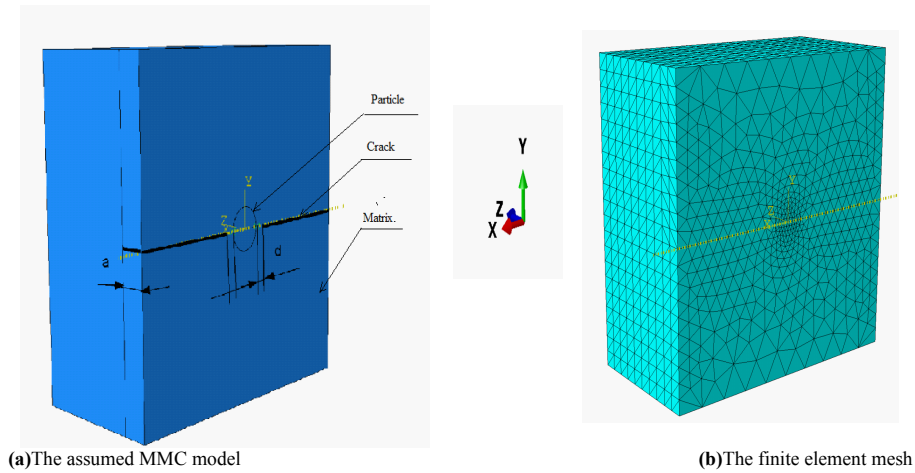
Properties	Matrix (Al)	Particle (SiC)
Material	elastic-plastic	isotropic elastic
Modulus of elasticity	70(GPa)	408(GPa)
Poisson ratio	0.3	0.2
Yield strength	275	/
CTE	23.4x10-6( $^{\circ}\text{C}^{-1}$ )	12.5x10-6( $^{\circ}\text{C}^{-1}$ )

This composite has been subjected to a thermal cycle of preheating to  $T_0$  followed by cooling to the ambient temperature. It is assumed that the absolute temperature field is homogeneous and that its evolution given by:

$$T(t) = T_0 + \tilde{T}.t \quad (1)$$

Where  $T_0$  is the initial temperature,  $t$  is time and  $\tilde{T}$  is the temperature rate, which is considered constant during cooling. Here, the initial temperature is considered for several cases  $T_0 = 120^{\circ}\text{C}$ ,  $220^{\circ}\text{C}$ ,  $320^{\circ}\text{C}$ ,  $420^{\circ}\text{C}$ ,  $520^{\circ}\text{C}$  and  $620^{\circ}\text{C}$ , whereas the final temperature is maintained equal to the ambient temperature ( $T_{\text{end}} = 20^{\circ}\text{C}$ ), and the constant cooling rate was considered  $\tilde{T} = -100^{\circ}\text{K S}^{-1}$ .

The calculations were performed using “ABAQUS “version 6.11. due to stress concentration, the precision of numerical method is strongly related to the quality of the designed mesh surrounding the particles and also to the zone containing the crack. Therefore, a 4 node linear tetrahedron (C3D4) finite element was used for modeling. The accuracy of the model was verified by comparing stress results with two other mesh densities, one with twice the number of elements and one with a coarse mesh having half the number of elements. The satisfactory model containing a spherical inclusion consists of 54625 elements shown in figure 1 b. Residual stresses fields were determined in Al (SiC) composites with 20 per cent volume fraction of reinforcement material.



**Figure 1** Modeling a particle-reinforced composite

### 3. Results and discussion

#### 3.1. *Stress distribution in the vertical orientation during thermal simulation at ( $\Delta T = 300^\circ\text{C}$ )*

The increase of the residual stresses between matrix and particle depend on the disagreement of the thermal expansion coefficient (CTE) and the modulus of elasticity and the coefficient of the fish between the matrix (Al) and the particle (SiC). Thus, the mismatch between the elasticity / plastic characteristics and the thermal expansion of the matrix and particle leads to an inhomogeneous plastic yield during thermal loading. This imbalance causes large stresses in the particles.

In the Figure 2 shows the distribution of Von mises and normal residual stress of the MMC when at  $\Delta T = 300^\circ\text{C}$ . I noticed higher stress are introduced at the vicinity of the matrix–particle interface, these stresses are devlopper by traction or compression between matrix and particle as previously mentioned by disagreement of the characteristics between matrix and particle.

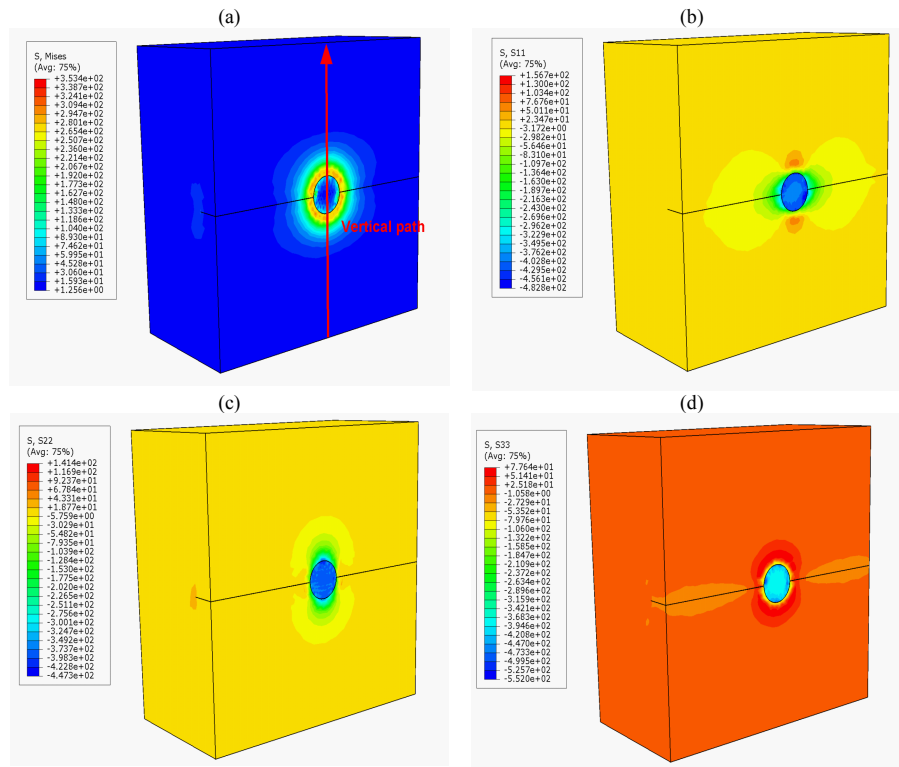
This stress decreases radially away from the center of the particle and tends to a negligible value to the extremity of the elementary volume.

From the distribution of the normal stresses along the z axis (Fig. 2.d) we notice clearly that the tensile stresses distribution in the matrix is homogeneous and the spherical with respect to center of the particle whose values are comparable to the stresses  $\sigma_{xx}$ . The compressive stresses are in the interior of the particle and are of the order of five times greater than those of the tensile. Far from the particle, this stress takes low values in the matrix.

Fig. 3a shows the corresponding distribution Von Mises stress in the matrix for a composite cool down from melting temperature ( $620^\circ\text{C}$ ) to room temperature ( $20^\circ\text{C}$ ). for the finite element method simulation at Width crack  $10\ \mu\text{m}$  and  $0.5\ \mu\text{m}$  interdistance. High Von Mises stress is developed in the particle, particle/matrix interface. The composites with higher SiC content exhibited higher Von Mises stress. The higher the reheating temperature, the greater the Von Mises stress

will be. These residual stress distributions are symmetrical about the axis vertical, showing the local influence of the indentation of the impactor.

The stress in a typical unit cell model three dimensions are shown in the Fig. 3 which shows the two kind of stress distribution after the cool-down from the melting temperature i.e. radial stress and hoop stress. Radial and hoop stresses act as compressive and tensile forces at interface in between the particle and matrix respectively.

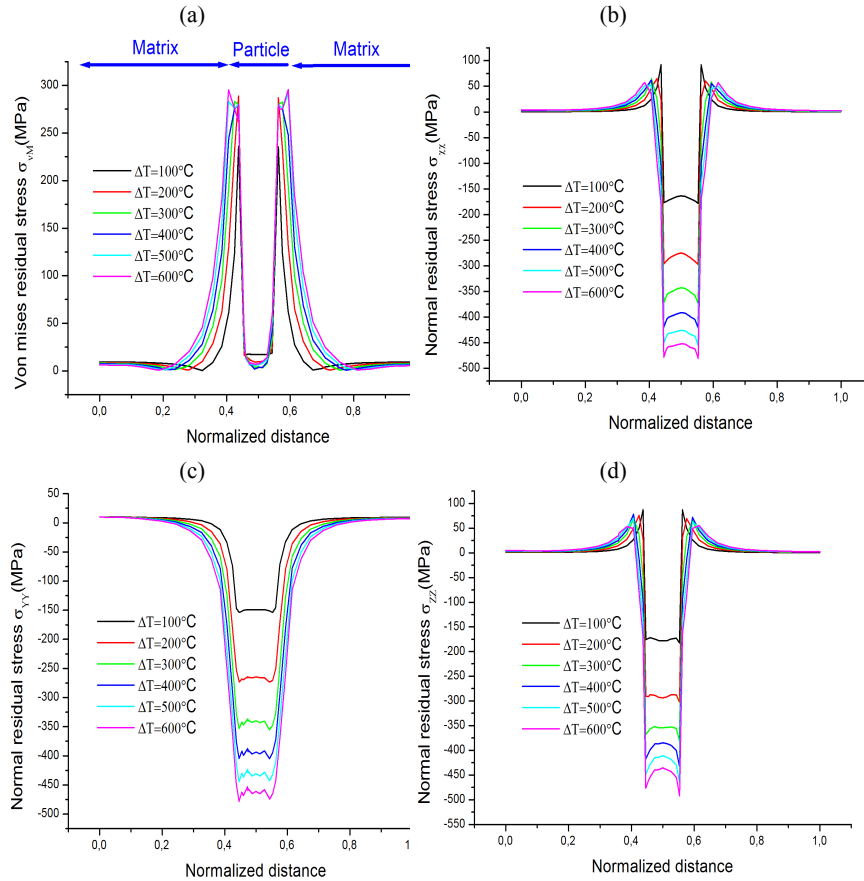


**Figure 2** Von-Mises and normal residual stress distribution (double-crack) for:  $d = 0.2 \mu\text{m}$ ,  $a = 10 \mu\text{m}$  at:  $\Delta T = 300^\circ\text{C}$ : a)  $\sigma_{vm}$ , b)  $\sigma_{xx}$ , c)  $\sigma_{yy}$  and d)  $\sigma_{zz}$

The distribution of normal residual stresses of Fig. 3b following x (longitudinal direction of the model). The model is subjected to a state of compression on the face opposite to the impact and to a state of traction along the y-axis (transverse direction of the model) of figure.3c a tensile pressure force of 10MPa is applied on the upper surface plane is quite logical. These residual stress distributions are symmetrical about the axis y.

The distribution of the normal residual stress following z is given of figure 3d. Almost the entire thickness of the model is in compression, MMC composites have a better resistance in compression than in tension. The current results show that the

values normal internal stresses introduced in the matrix and the particle increase with increasing the reheating temperature.



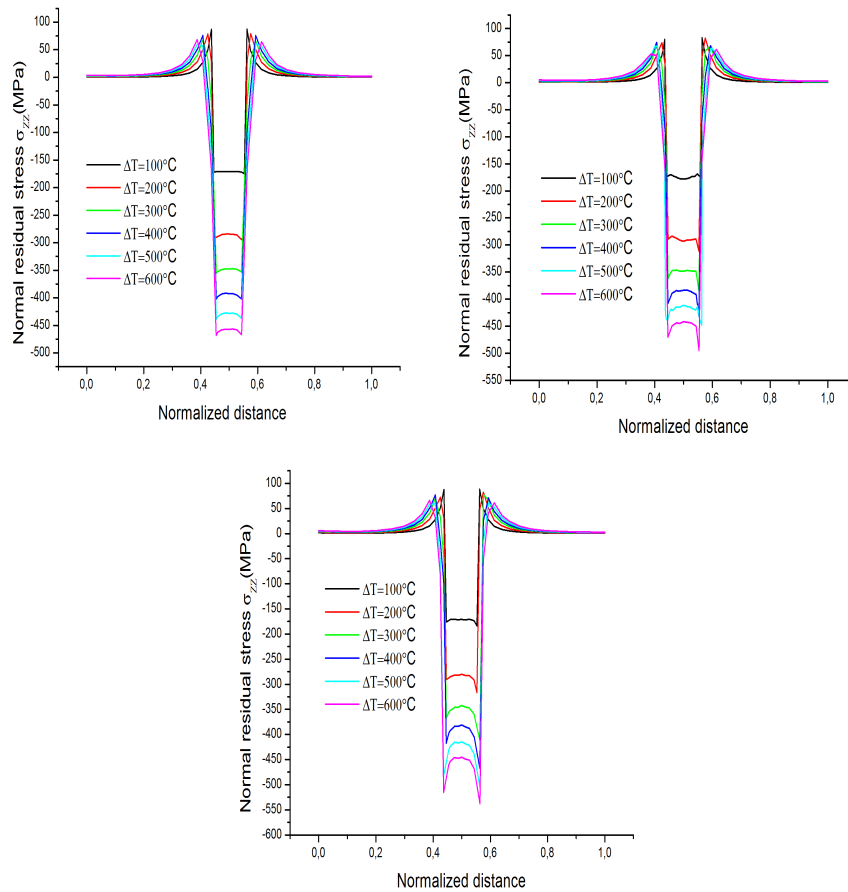
**Figure 3** Von-Mises and normal residual stress distribution (double-crack) for:  $d = 0.5 \mu\text{m}$ ,  $a = 10 \mu\text{m}$ , a)  $\sigma_{vm}$ , b)  $\sigma_{xx}$ , c)  $\sigma_{yy}$  and d)  $\sigma_{zz}$

### 3.2. The effect of the size crack longitudinal on the matrix and particle

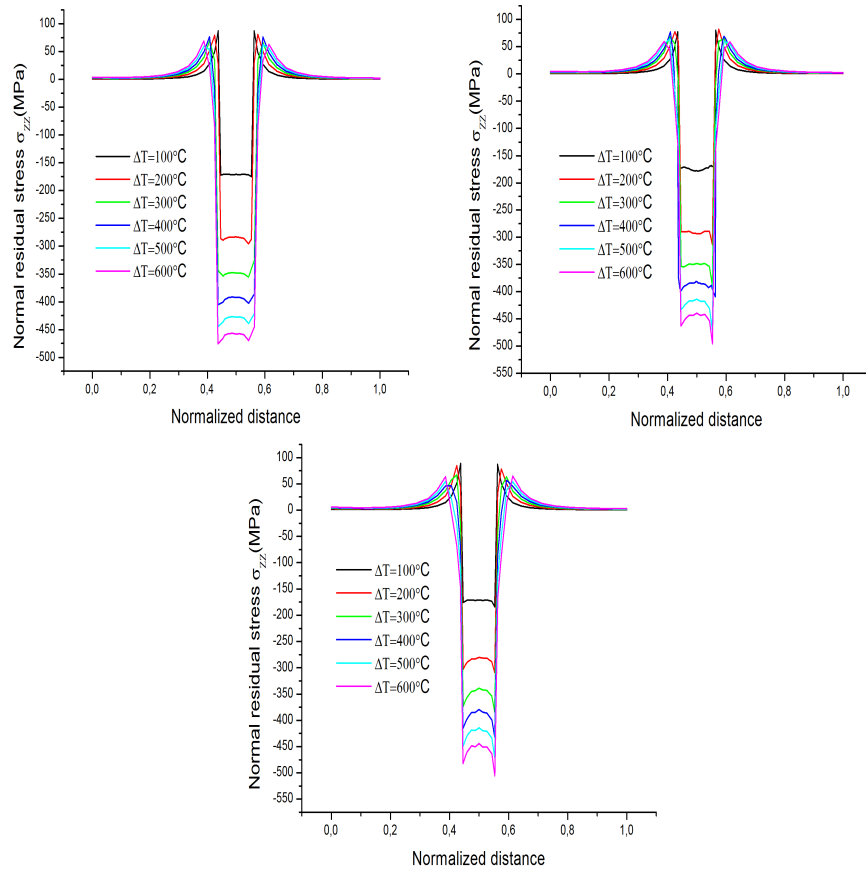
Since the residual stresses are greater along the z-axis, I calculate this axis for three penetration penetrations for inter-distance:  $d = 0.1 \mu\text{m}$ ;  $d = 0.2 \mu\text{m}$  and  $d = 0.5 \mu\text{m}$ , and crack width  $a = 5 \mu\text{m}$ ;  $a = 10 \mu\text{m}$  and  $a = 15 \mu\text{m}$ . After observing the three calculation penetrations (the curves presented in Figures 10 to 18) the residual stress values are higher than those obtained in the case of the single crack (Nehari et al [13]). This means that the double crack generates additional residual stresses. Figures. 4, 5, 6 illustrates the variation of the normal residual stresses with respect to the z axis. increasing the width of the crack leads to an increase in residual stresses.

The inter-distance between crack and particle plays an important role for the generation of residual stresses. The shorter the inter-distance (closer to the particle), the higher the normal residual stresses of the next  $z$ . (See Table 3, 4 and 5).

I noticed that the larger the crack width ( $a$ ), the larger the subsequent residual stress ( $z$ ) increased. (See Table 3, 4.5).



**Figure 4** Normal residual stress distribution  $\sigma_{zz}$  for:  $d = 0.1 \mu\text{m}$ , (a)  $a = 5 \mu\text{m}$ , (b)  $a = 10 \mu\text{m}$ , (c)  $a = 15 \mu\text{m}$

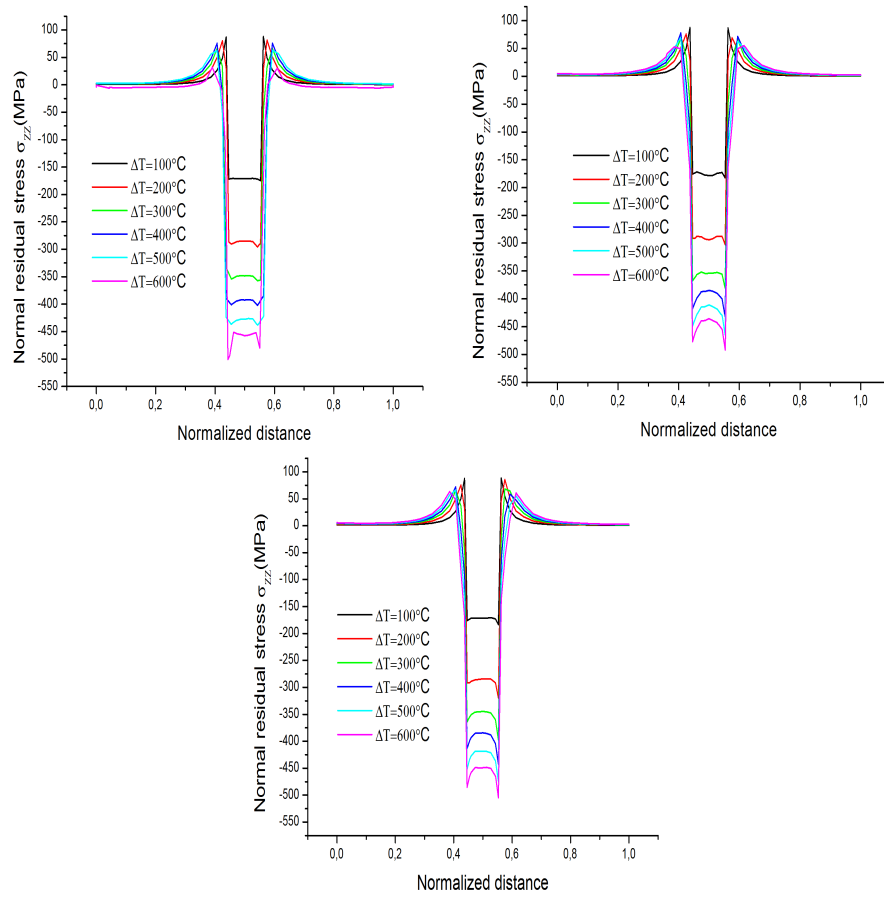


**Figure 5** Normal residual stress distribution  $\sigma_{zz}$  for: d = 0.2  $\mu\text{m}$ , (a) a = 5  $\mu\text{m}$ , (b) a = 10  $\mu\text{m}$ , (c) a = 15  $\mu\text{m}$

**Table 3** Residual stress maximal  $\sigma_{zz}$  for d = 0.1  $\mu\text{m}$

Width for crack a [ $\mu\text{m}$ ]	5	10	15
Residual stresses $\sigma$ max [MPa]	-468	-490	-538





**Figure 6** Normal residual stress distribution  $\sigma_{zz}$  for:  $d = 0.5 \mu\text{m}$ , (a)  $a = 5 \mu\text{m}$ , (b)  $a = 10 \mu\text{m}$ , (c)  $a = 15 \mu\text{m}$

**Table 4** Residual stress maximal  $\sigma_{zz}$  for  $d = 0.2 \mu\text{m}$

Width for crack $a$ [ $\mu\text{m}$ ]	5	10	15
Residual stresses $\sigma$ max [MPa]	-475	-495	-504

**Table 5** Residual stress maximal  $\sigma_{zz}$  for  $d = 0.5 \mu\text{m}$

Width for crack $a$ [ $\mu\text{m}$ ]	5	10	15
Residual stresses $\sigma$ max [MPa]	-500	-502	-503

#### 4. Conclusions

In the present study, to determine the influence of double crack penetration and gradient temperature on the generation of residual thermal stresses and mechanical behaviour for the Al–SiC composite. Findings from this Investigation are listed below:

1. Inter-distance between crack and particle plays an important role regarding the generation of residual stresses. The lower the inter-distance, the higher the internal stresses of normal residual stresses of  $\sigma_{zz}$ .
2. The level of equivalent internal stress of Von Mises stress and normal residual stresses for double crack is more significant as the crack alone.
3. I noted that the larger the crack width of 5  $\mu\text{m}$ , 10  $\mu\text{m}$  and 15  $\mu\text{m}$ , plus the residual stress of  $\sigma_{zz}$  increased.
4. The values normal internal stresses introduced in the matrix and the particle increase with increasing the reheating temperature.
5. Extensive residual stresses are generated, mostly at the interface matrix, particle.
6. A double increase in reheating temperature resulted in a double increase in equivalent stress as well.

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### Nomenclature

$d$  – Inter-distance between crack and particle

$a$  – width of crack

$V_M$  – Von Mises

$\sigma_{xx}$  – Normal residual stress next xx

$\sigma_{yy}$  – Normal residual stress next yy

$\sigma_{zz}$  – Normal residual stress next zz

$Al$  – Aluminum

$SiC$  – Silicon carbide

$T_0$  : Temperature rate

$\tilde{T}$  – Final temperature

$T_{end}$  – ambient temperature

$t$  – Time

