Influence of thermal residual stress on behaviour of metal matrix composites reinforced with particles

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Abstract. The properties of a metallic matrix composites materials (MMC’s) reinforced with particles can be affected by different events occurring within the material in a manufacturing process. The existence of residual stresses resulting from the manufacturing process of these materials (MMC’s) can markedly differentiate the curves obtained in tensile tests obtained from compression tests. One of the themes developed in this work is the influence of residual stresses on the mechanical behaviour of these materials. The objective of this research work presented is numerically estimate the thermal residual stresses using a unit cell model for the Mg ZC71 alloy reinforced with SiC particles with volume fraction of 12% (hot-forging technology). The MMC’s microstructure is represented as a three dimensional prismatic cube-shaped with a cylindrical reinforcing particle located in the centre of the prism. These cell models are widely used in predicting stress/strain behaviour of MMC’s materials, in this analysis the uniaxial stress/strain response of the composite can be obtained through the calculation using the commercial finite-element code.

1. Introduction
Metal matrix materials MMC’s show, besides light weight, excellent mechanical behaviour (raised Modulus of Elasticity), also has good wear characteristics and a lower coefficient of thermal expansion than magnesium alloys [1-4]. These materials are generally composed by a metal matrix (Mg or Al alloy based) and reinforcements of fibres or ceramic particles. The Matrix provides the shape to the structural element and transmit stress to the reinforcement, which in turn bears the stress transfer by the matrix [5-7]. This paper reports the results of a numerical investigation of the influence of thermal residual stress on behaviour of metal matrix composite reinforced with ceramic particles (SiC, 12% vol). The global response of a unit cell model [8-10] is then studied under four load conditions; (1) uniaxial tensile loading, with residual stress/strain via a temperature drop; (2) uniaxial tensile loading, without residual stress (3) uniaxial compressive loading, with residual stress, (4) uniaxial compressive loading, without residual stress.

2. Material
Table 1 shows the coefficients of dilatation and specific heats of SiC for both materials. Due to particles addition in the ZC71-matrix, it is observed a change of the coefficients of thermal expansion and conductivity K. These coefficients will change the temperature increase depending of the material used. The temperature drop that occurs when cooling from the processing temperature down to the working temperature results in large residual thermal stresses/strains due to the large difference in the coefficients of thermal expansion.
The following parameters have been derived from experimental curves $\sigma$-$\varepsilon$: Young’s modulus ($E$) and elastic limit ($\sigma_y$) (Figure 1).

### Table 1. Thermal properties (source: MELRAM composite, U.K.).

| Material | $\alpha (K^{-1})$ | $c (Kg^{-1}K^{-1})$ |
|----------|-------------------|---------------------|
| SiC      | $4.3 \times 10^{-6}$ | 840                 |
| Mg       | $26 \times 10^{-6}$  | 1025                |

3. Numerical simulations

A three-dimensional numerical model was used to simulate the deformation process by cooling from the processing temperature 728K (455°C) (the annealing temperature) down to 296K (23°C) (room temperature). The numerical model includes the specimen geometry “cubic unit cell” with the two parts corresponding to the matrix Mg and the particle in contact “Tie”. With this numerical model were simulated four load conditions (1) uniaxial tensile loading, without residual stress; (2) uniaxial tensile loading, with residual stress/strain via a temperature drop; (3) uniaxial compressive loading, without residual stress and (4) uniaxial compressive loading, with residual stress. The numerical simulations were performed using the commercial finite-element code ANSYS. Different mesh sizes were considered in order to analyse the mesh sensitivity and to define the optimum one (2240 element and 2745 nodes for the matrix; 7328 element and 3971 nodes for the SiC particle, reduced integration hexahedral elements with eight nodes) (Figure 2(a)). The calculation is performed using a commercial code of finite elements, by implementing the Matrix constitutive law, following a thermoelasto-viscoplastic behaviour.

![Figure 2](a) Meshing numerical model. (b) Part Assembly the unit cell model.

4. Results and discussions

4.1. Residual stress

Figure 2(a), 2(b), displays the zones that were considered to have a more relevant stress distribution. Sections A-A and B-B are in the most singular zone of the unit cell, which is the reinforcement-matrix interface. This zone produces a high concentration of stresses. Figure 3 shows the variation of the...
equivalent stress in section AA, as a function of the distance to the cell axis. On the left half side of the
Figure 3, the corresponding curves of the equivalent stress in the reinforcement and matrix are
overlapped. It can also be observed a rapidly increase in the stress of the reinforcement up to the sharp
edge, while the variation of stress in the matrix remains almost constant with changes to the distance
from the corner, except far from the reinforcement, where there is a steep drop.

Figure 4 shows the variation of the equivalent stress in section BB, as a function of the distance to
the cell axis. On the left half side of the figure, the corresponding curves of the equivalent stress in the
reinforcement and matrix are overlapped. It can also be observed a rapidly increase in the stress of the
reinforcement up to the sharp edge, while the variation of stress in the matrix remains almost constant
with changes to the distance from the corner, except far from the reinforcement, where there is a steep
drop.

![Figure 3. Equivalent stress distribution across AA.](image1)

![Figure 4. Equivalent stress distribution across BB.](image2)

Figure 5 shows the stress $\sigma_{zz}$ in section AA, as a function of the distance to the cell axis. On the left
half side of the graph, the corresponding curves of the stress $\sigma_{zz}$ in the reinforcement and matrix are
overlapped. It can be observed that the stress in the reinforcement and matrix are very similar, and
correspond to the applied mutual compression. The stress in the matrix experiences a steep drop from
the negative numbers, associated to the matrix-particle compression, to the positive numbers.

![Figure 5. Stress $\sigma_{zz}$ across AA.](image3)
4.2. The influence of the loads conditions
First, a field of residual stresses with thermal origin has been obtained as a result numerical of the cooling phase. Second, it has been applied to the particle model with and without residual stresses of thermal origin, a load condition (load condition 1 and 2) with a value lower than the elastic limit of the material after obtaining the enlargement $\Delta L$ of the particle-matrix (cell) set. Table 2 presents values for the elastic modulus obtained in the two mentioned situations (load condition 1 and 2): With and without previous residual stresses (equivalent to have carried out a thermal treatment that could eliminate them). It can be observed that the difference between both values of the elastic modulus is 13%, as a consequence, this difference to the mesoscopic residual stresses of thermal origin.

|                      | $E$ (Gpa) tensile | $E$ (Gpa) compression |
|----------------------|------------------|-----------------------|
| With residual stresses | 47               | 43                    |
| Without residual stresses | 54              | 54                    |

In order to provide all the information about the influence of residual stresses on the elastic modulus $E$, this was also calculated based on the deformation reached after applying to the cell a compression stress with a value lower than the elastic limit. In order to isolate the effect of the field of residual stresses from other mechanical effects (possible difference of the behaviour in tension and compression), the same stress-strain law has been applied to the matrix material. Table 2 shows the values for the elastic modulus obtained in the two mentioned situations (load condition 3 and 4): With and without previous residual stresses (equivalent to have carried out a thermal treatment that could eliminate them). It can be observed that in the absence of residual stresses, the obtained Young’s modulus are the same. However, if a previous state of residual stress exists, the values obtained for the elastic modulus are different, thereby obtaining a lower value during a compression test.

The following conclusions of the cell model are drawn from the results presented here:

- Allow to obtain, with notable accuracy, the field of residual stresses in the particle-matrix interface.
- Allow to reflect specific conditions like particle geometry, the proportion in volume, and interface characteristics.
- The numerical values for the mechanical parameters obtained using cell models, clearly show trends and influences of other parameters and conditions. However, there is some disagreement with experimental values. These differences could be due to an incorrect selection of the boundary conditions applied to the model.

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