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Thermomechanical Modelling Of Copper Matrix Composites Reinforced With Tungsten Fibres

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Abstract. The purpose of this work is to investigate and understand the thermomechanical behaviour of copper matrix composites with long fibres. The effects of the volume fraction of fibres are considered in this analysis. A micromechanical finite element model has been used to study the behaviour of the copper matrix composites reinforced with tungsten fibres, which undergo thermal cycling conditions. Furthermore, regular and random arrangements of fibres are considered.

Introduction. Metal matrix composites are potential candidates for high temperature applications, for example, as heat sinks in thrust chambers. These composites should be able to keep their original dimensions, when subjected to thermal and mechanical loads. The thrust chambers undergo thermal cycles in service, which induce deformation in the material. Thereby, thermal cycling in the composites can result in interfacial debonding along the matrix/fibre interface [1]. Excellent thermal conductivity is an important material property for composites that should be considered [2]. Therefore, copper matrix composites reinforced with tungsten fibres are proposed to be used in high temperature environments [3]. Experimental investigations on copper matrix composites reinforced with long fibres have been performed by various researchers [4-6]. Moreover, analytical and numerical methods have been used to understand the behaviour of composites [6, 7]. Rangaswamy *et al* [8] and Misra [9] used the concentric cylinder model to estimate the residual stresses in the long fibre. Ozdemir and Toparli employed the finite element method to study the stress-strain relationship and thermal behaviour of composites under thermal cycling conditions [10]. A micromechanical finite element model has been used to understand the thermomechanical behaviour of the copper matrix composites reinforced with long tungsten fibres, under thermal cycling conditions. The stresses developed in the matrix, due to thermal cycling, cause plastic deformation in the matrix [5]. This behaviour can be observed in others composites systems [9]. The effect of the neighbouring fibres causes a variation in the stress level from tensile stress to compressive values [11].

Micromechanical modelling. The copper matrix composites reinforced with tungsten fibres provide a strong and stable interface, since tungsten and copper are mutually insoluble, and the copper wets well to the tungsten [6,7,12,13]. Therefore, the W/Cu interface is considered as a perfectly bonded interface as a first approximation in the simulation and no reaction zone is modelled at the interface. Thermal residual stresses are generated during the solidification of the composite. Thus, thermal residual stresses are considered: a stress free-temperature of 900 ºC is assumed in the model (10 K/min). The thermal cycling simulation ranges from room temperature to the operation temperature (550 ºC) corresponding to the industrial application. Uniform temperature is applied in the whole unit cell. The thermal simulation sequence

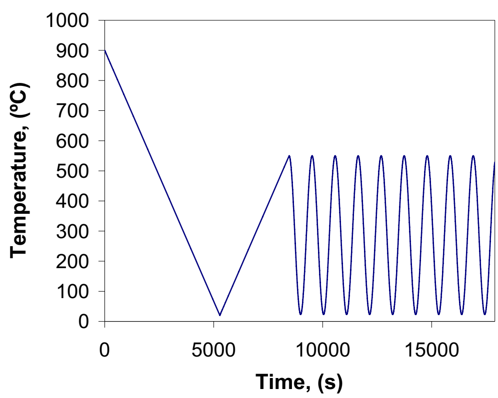

Figure 1. Thermal history

is shown in figure 1. Regular and random distributions of fibres are used in the micromechanical modelling in order to study the influence of the thermal stresses in the composites. The macrostresses in the unit cells are calculated as the volume-averaged of the corresponding microstress component [14]:

$$\overline{\sigma_{f,m}} = \frac{1}{V_{f,m}}\left[\sum^{N}\sigma^{k}_{f,m}\,V^{k}_{f,m}\right], \qquad \overline{\varepsilon_{f,m}} = \frac{1}{V_{f,m}}\left[\sum^{N}\varepsilon^{k}_{f,m}\,V^{k}_{f,m}\right]. \tag{1}$$

where V is the total volume , V^k is the volume of the k-th element, σ is the volume-averaged stress in the k-th element, ε is the volume-averaged strain of the k-th element and $N_{f,m}$ is the total number of elements (f=fibre, m=matrix).

Boundary conditions. The model employs generalised plane strain elements to allow modelling composites reinforced with long fibres. Periodic conditions are applied: the upper and right edges of the unit cell are constrained to have uniform displacements. Symmetry conditions are imposed in the other edges. Figure 2 shows a schematic of the unit cell for a regular array of fibres. On another hand, random distributions of fibres are generated by means of a program in MATLAB© software [15]. The overlapping of fibres is not permitted and appropriate boundary conditions are imposed. Figure 3 shows the random fibres arrays employed in the analysis.

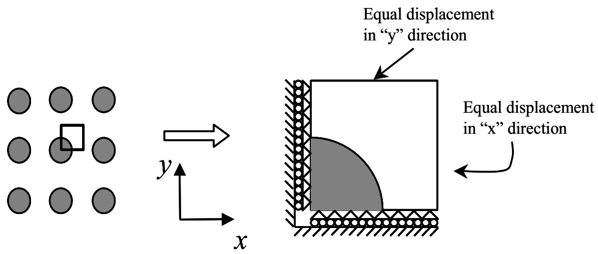

Figure 2. Boundary conditions for a regular arrangement of fibres

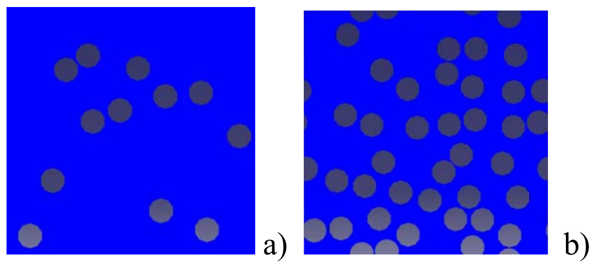

Figure 3. Random fibres arrays:
a) 9% and b) 50% volume fraction

Material properties. The assumed diameter of the tungsten fibre is 100 μm. The fibres and the matrix are considered to have temperature-dependent and elastic-plastic behaviour. Stress-strain data curves introduced to the model are from [16]. Additionally, a power-law creep has been included in the copper matrix as a user subroutine, which takes into account the creep behaviour at various temperatures. Figure 3 shows the material properties employed in the model. An acceptable curve fitting is used to reduce the parameters in the power-law equation:

$$\dot{\varepsilon} = A\sigma^{n}\exp\left(\frac{Q}{RT}\right). \tag{2}$$

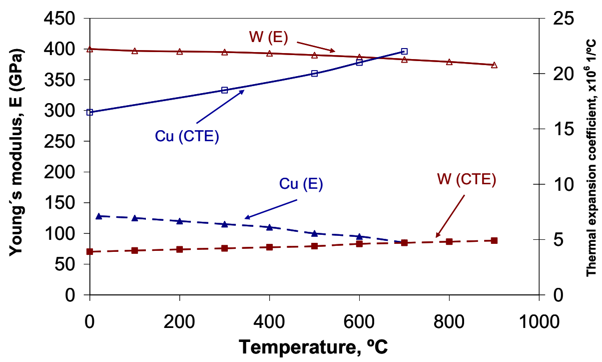

Figure 4. Modulus of elasticity (E) and coefficient of thermal expansion (CTE) for copper and tungsten

where $\dot{\varepsilon}$ is the creep strain rate (1/s), σ is the Mises equivalent stress (Pa), Q is the activation energy, R is the gas constant, T is the melting point (K), n is an exponent and A is a constant.

Results and discussion

Fibre arrangements effect in the composite. Axial and transverse thermal stresses are higher for random distributions than for a regular arrangement of fibres at room temperature (as shown in figure 5). The averaged axial stress developed is compressive: 18 MPa and 21 MPa at 550 ºC, for regular and random distributions respectively (in the case of the copper matrix reinforced with 30% volume fraction of fibres). The thermal transverse stresses, in regular and random arrangements, are 3.4 MPa and 8 MPa, respectively.

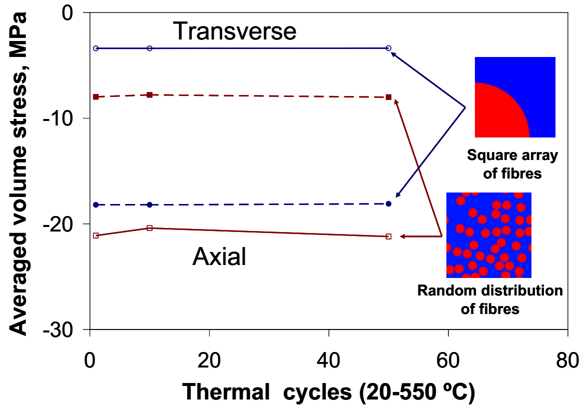

Figure 5. Volume-averaged axial stress with regular and random fibres arrangements (30%W)

Volume fractions effect of tungsten fibres. During the cooling process, the copper matrix yields at 712 ºC, and the von Mises stress developed is 40 MPa. The maximum von Mises stress reached is 55 MPa, at room temperature, as shown in figure 6. On the other hand, axial stresses are homogeneous in the matrix at low volume fractions, because there is little influence from the neighbouring fibres (for example 9% volume fraction of tungsten fibres). However, as volume fraction increases, the compressive axial stress (of the copper matrix) increases until reaching 80 MPa. Figure 7 shows the axial stresses in the copper matrix, at room temperature, for various volume fractions of tungsten fibres. Later, the copper matrix composite is heated to the operation temperature (550 ºC). Significant transverse stresses are developed between fibres. These zones are prone to debonding at the fibre/matrix interface. Figure 8 shows the contours of the transverse stresses distributions in the copper matrix, for 9 and 50% volume fractions of fibres. Maximum stresses are located between fibres. The stresses increase when space between fibres is decreased.

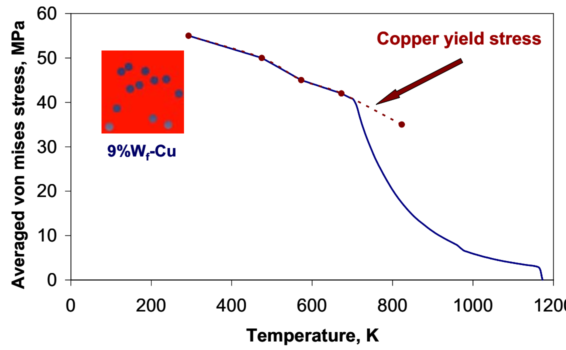

Figure 6. Temperature – Volume-averaged von Mises stress of composite with 9% of tungsten fibres

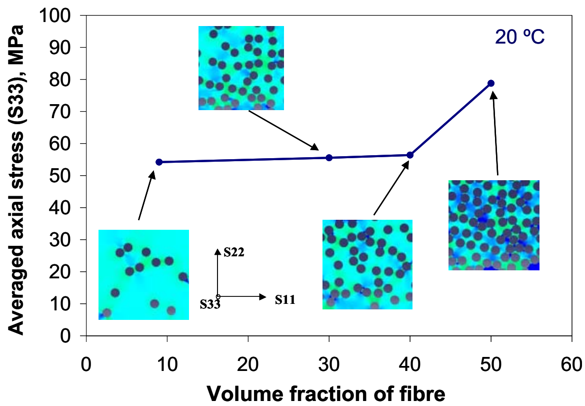

Figure 7. Volume-averaged axial stress at 20 ºC (after cooling from manufacture temperature, 900 ºC)

Thermal cycling. Figure 9 shows the volume-averaged axial and transverse stress of the copper matrix at 550 ºC, for various volume fractions (during thermal cycling from 20 to 550 ºC). In the case of a Cu matrix, with 50% volume fraction, the compressive axial stress increases from 21 MPa to 26 MPa, after ten thermal cycles. The volume-averaged thermal stress is higher in the axial direction than in the transverse direction. Maximum stresses are located near the fibres: for example, the axial stress is 55 MPa for a composite with 9%W_f volume fraction, and 173.81 MPa for a Cu matrix reinforced with 50%$W_{f,}$ both at the first thermal cycle (@ 550 ºC). In the case of the composite with 50%$W_{f,}$ as the copper matrix undergoes thermal cycling from 20º to 550º C, the stresses decrease from 173.81 MPa (cycle 1) to 155 MPa (cycle 50). Figure 10 shows axial stress developed in the matrix, near tungsten fibres. The stresses increase as the volume fractions of fibres are increased. Therefore, the probability of fibre/matrix interface debonding rises considerably.

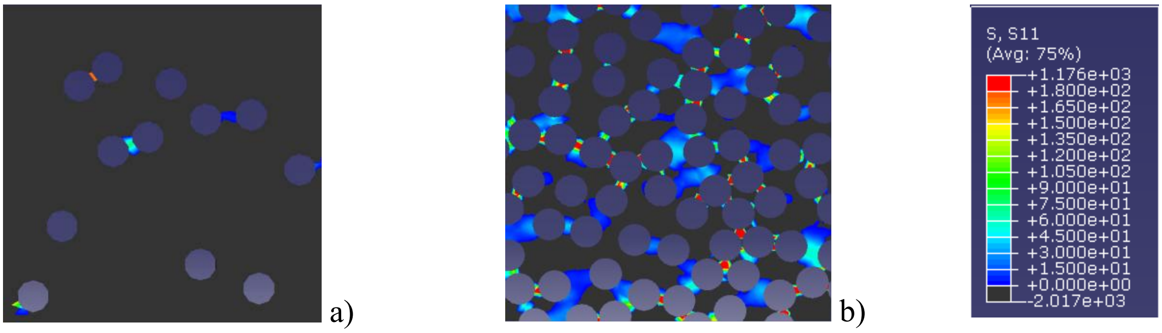

Figure 8. Transverse stresses in the copper matrix at 500 ºC: a) 9% and b) 50% of tungsten fibres

Summary. Unidirectional copper matrix composites, when subjected to thermal loading, are investigated using the finite element analysis. Residual stresses are taken into account by simulating the cooling stage, from manufacturing temperature to room temperature. Creep behaviour of copper is introduced in the model. Uniform temperature is assumed over the models during the analysis. The effect of fibre arrangements are studied, by means of regular and random arrays. Various volume fractions of fibres are studied.

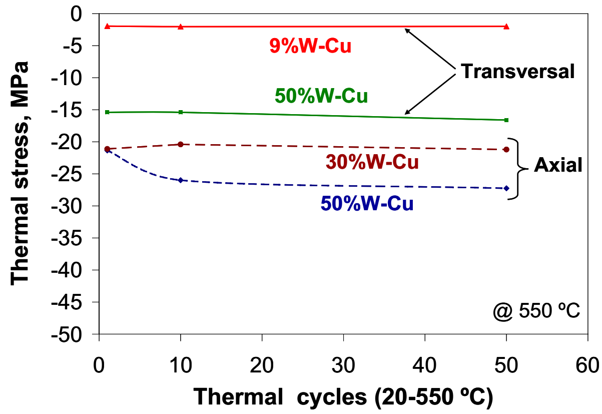

Figure 9. Volume-averaged thermal stress in copper matrix reinforced with tungsten fibres randomly distributed

Thermal stresses generated during thermal cycles in the composite are larger for the random distribution than for the regular arrangement of fibres. Thereby, the possibilities of the matrix/fibre interface debonding increase in the shorter distance between fibres, during thermal cycling. After the cooling process, high plastic deformation can be observed around fibres, while for isolated fibres, the stresses decrease. The influence of thermal stresses on the copper composite is dependent on the fibre distribution. The internal stresses, between the fibres and the matrix, generated during the thermal cycling (due to difference in coefficients of thermal expansions) are enough to cause the matrix to yield. The copper matrix yields at 712ºC during the cooling stage. Later, the copper matrix still deforms plastically. Significant stresses are observed near the interface during thermal cycling, in a W-Cu composite. The largest stresses in the matrix are located at the region between fibres. This is attributed to the interaction of neighbouring fibres, which increase the stresses at the matrix region between these fibres [14].

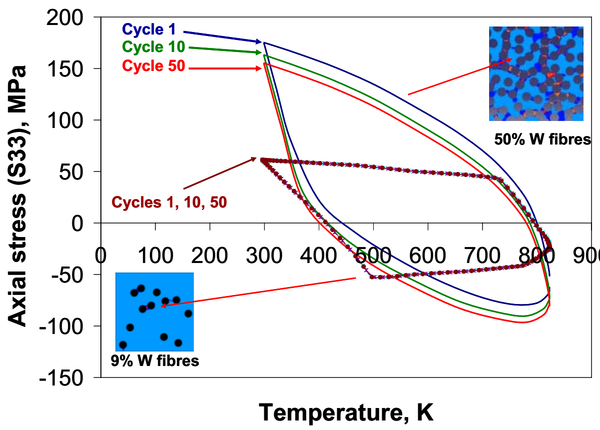

Figure 10. Axial stress in Cu matrix reinforced with 9 and 50 % of tungsten fibres

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