
CRACK PATTERN OF A COMPOSITE MODEL MATERIAL SUBMITTED TO A TEMPERATURE INCREASE ASSISTED BY DIC

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Abstract. *Internal stresses may arise in composite systems in reason of the phase's coefficient thermal expansion (CTE) mismatch when it is submitted to a temperature variation. Several works have discussed this phenomenon to understand the parameters that influence the internal stresses in composite materials resultant from the temperature variation [1, 2, 3]. These works have analyzed the resultant failure of composite systems or evaluated the parameters evolution related to the temperature variation. This paper brings the results of experiments conducted in a model composite submitted to temperature variation assisted by the Digital Image Correlation (DIC) technique. The main purpose of this article is to bring experimental field information of the crack nucleation and growth relating the composite phase's properties and the system temperature variation with the cracks nucleation and propagation in this model composite system via the DIC technique. For that, a material system was chosen and characterized, being a calcined alumina and colloidal silica mortar the matrix and brass cylinders the discontinuous phase. A manufactured process was developed for the model composite. Two different modalities of experiments were conducted: (i) experiments for the mechanical (Brazil disc test) and thermomechanical (Optical dilatometry) characterization of the materials that composes each phase of the model composite; (ii) experiments to crack the model composite via temperature variation. All the experiments were assisted by the DIC technique to obtain field information enriching the experiments results. The model composite presents a radial crack pattern with the crack nucleation starting from a temperature variation of 100 °C. The crack was nucleated in the matrix inclusion interface. The crack pattern evolution and the criteria for the crack initiation are based in the post processing of the principal maximum strain obtained by the DIC technique.*

1. INTRODUCTION

The engineering industry employs composite materials in applications where the performance and costs requirements cannot be satisfied using standard materials. Nowadays, industrial sectors such as aerospace, naval, automotive and medical increasingly make use of composites, for example, the Boeing 787 Dreamliner uses more than 50% wt of composites in its airframe[4]. There are applications that require materials with high mechanical strength for high-temperature environments, as in leading edges of supersonic aircraft, and heat shields of space shuttles [5]. The combination of different materials to obtain the most suitable properties concerning its constituents is a complex task since the interaction

between the phases can lead to undesired behavior. The macroscopic properties of a composite depend on several factors like the interface among the phases, the volumetric fraction, and the properties mismatch of its constituents [1, 2, 3]. For a better comprehension of how a composite behaves when exposed to loads mechanical and hygrothermal loads, analytical and computational tools are developed, and experimental tests performed [1-3, 6-9].

In the experimental field, model materials allow elucidating some complex phenomena like the structural failure due to the constituent's properties misfit. Several literature studies report the use of model materials to improve the understanding of complex material behavior [2, 3, 10, 11]. When a material is submitted to a temperature variation, the mismatch between the coefficient of thermal expansion (CTE) leads to internal stresses that can lead to material failure, making the materials combination unfeasible for a desired application or even wanted for other ones [11]. Using model materials to understand complex mechanical behavior, the present article aims to investigate the mechanical behavior of a model composite submitted to a temperature variation that leads the system to crack. The experimental investigation is conducted by the measurements of the displacement fields, identification of the crack pattern and evaluation of the material crack initiation.

2. COMPOSITE FAILURE DUE TO TEMPERATURE VARIATION

The mismatch of the CTE between the composites phases leads to stress when the composite is submitted to temperature variation. Analysing a simplified system that consists of a biphasic model composite with only one inclusion embedded in a continuous matrix, depending on the CTE relation of the phases and the positive or negative temperature variation, a different stress distribution will be reached, and, with the material failure, different crack patterns achieved.

Selsing, described the interfacial radial pressure ($p_{(i/m)}$) between a spherical inclusion in an infinite matrix based on the pressure vessel equations as:

$$p_{(i/m)} = \frac{(\alpha_i - \alpha_m) \Delta T}{\frac{1 + \nu_m}{2E_m} + \frac{1 - 2\nu_i}{E_i}} \quad (1)$$

being α the CET, ν the coefficient of Poisson, E the Young's modulus, and the subscripts index i and m refers to the inclusion and matrix phase. Based on Selsing's equation, Davidge and Green propound a model to evaluate the strength for Selsing's model for a situation where the size of the fracture is well established, a matrix/inclusion debonding [2].

For a simplified system as the one described by Selsing's equation and considering the system under a positive temperature variation, if the CTE of the inclusion is greater than the matrix, a tangential tensile stress will arise on the matrix that can result in radial cracks, and If the CTE of the inclusion is lower than the matrix, a radial tensile stress will arise on the matrix that can result in circumferential cracks [2].

Zago described the calculus of the radial and tangential stress in a plane stress state for a system composed of a single cylindrical inclusion in an infinite matrix as [12]:

$$\sigma_{rr} = 2(Ai - \alpha_i \Delta T) \left(\mu_i + \lambda_i - \frac{\lambda_i^2}{\lambda_i + 2\mu_i} \right)$$

$$\sigma_{\theta\theta} = (\lambda_i + 2\mu_i)(Ai - \alpha_i \Delta T) + \lambda_i \left(Ai - \alpha_i \Delta T + \frac{2\lambda_i(\alpha_i \Delta T - Ai)}{\lambda_i + 2\mu_i} \right) \quad (2)$$

where

$$A_i = \frac{\alpha_i \left(\mu_i + \lambda_i - \frac{\lambda_i^2}{\lambda_i + 2\mu_i} \right) \Delta T + \alpha_m \mu_m \Delta T}{\mu_i + \lambda_i - \frac{\lambda_i^2}{\lambda_i + 2\mu_i} + \mu_m} \quad (3)$$

and λ and μ are the first and second Lamé parameters respectively. These stresses are directly related to the experiments conducted in this paper.

3. METHODOLOGY

3.1 Specimens manufacturing

Two types of specimens were manufactured: (i) for identification of the properties of interest; and (ii) for investigation of the mechanical behavior of a model material submitted to a temperature variation. The model composite designed consists of a cylindrical brass inclusion embedded in an alumina and colloidal silica mortar matrix. Cylindrical specimens were used for the identification of mechanical properties and the coefficient of thermal expansion of brass and alumina mortar. The identification of the mechanical properties was performed via diametral compression of a 73 mm diameter 10 mm thick alumina mortar disc, and a 63 mm diameter 8 mm thick brass disc. The coefficient of thermal expansion was measured using optical dilatometry tests.

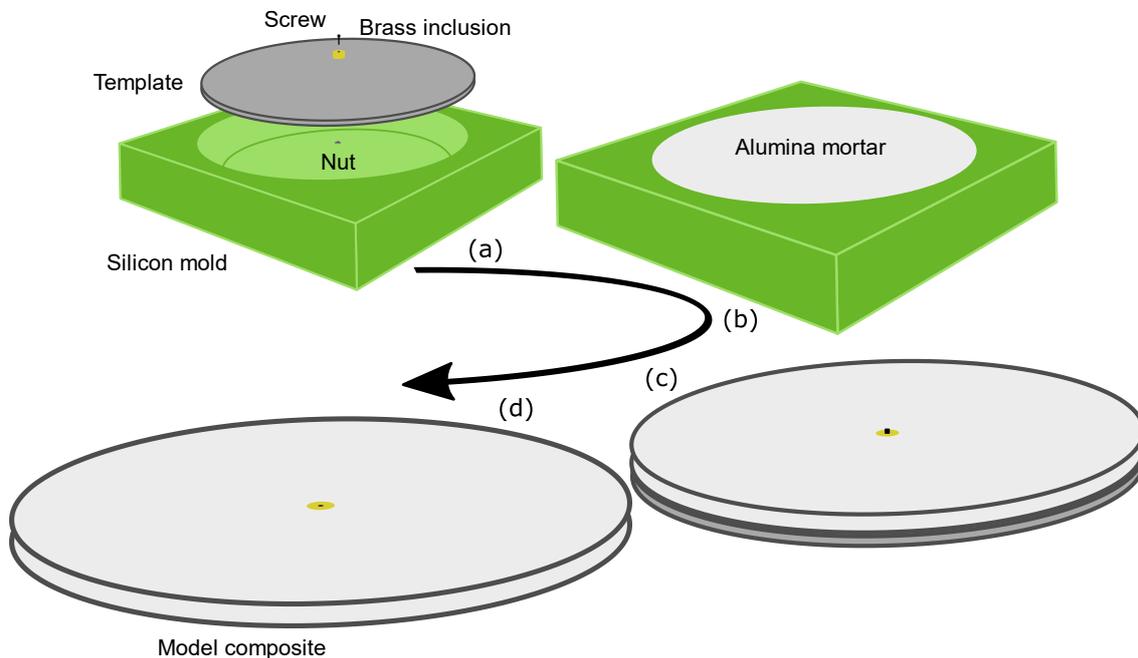


Figure 1 - Model material manufacturing route. (a) The inclusion is assembled to the template with a screw and nut. The assembly is put in the silicon mold. (b) The alumina mortar is poured in over the template and scattered with vibration. Then, the mold is moved to the oven and remains for two days in the temperature of 40 °C. (c) The template is removed from the mold and sanded to the screw inclusions surface. (d) The model composite is released from the template and is finished with sandpaper.

The displacement field was monitored using Digital Image Correlation (DIC) technique. The route indicated in Figure 1 was adopted to manufacture the model material. The model composite has 140 mm diameter and 8 mm thick. The 12.7 mm diameter brass inclusion is positioned at the specimen center. A 2 mm screw fixed the inclusion to an aluminum template that guarantees the inclusion positioning while the silicon mold was vibrated to accommodate the alumina mortar. All samples prepared with alumina mortar remain two days inside the oven in a temperature of 40 °C.

3.2 Identification of the mechanical and thermo-mechanical properties

3.2.1 Identification procedure

The Elastic modulus (E) and Poisson Coefficient (ν) of the matrix and inclusion materials are obtained from the post-processing of the DIC results of diametrical compression tests conducted in brass and alumina mortar samples. And the CTE of the materials are obtained via optical dilatometry tests. The displacement and strain fields provided by the technique can be used to identify different parameters with a single test. In both modalities of tests - mechanical and thermal - the material properties are reached via the minimization of the experimental displacement fields obtained via DIC and the close analytical solutions for the problems. It is conducted a quadratic difference minimization between the experimental displacement field (\mathbf{u}_{exp}) and the model displacement field (\mathbf{u}_{mod}) in the region of interest Ω , i.e.:

$$\mathcal{F}(\mathbf{p}) = \int_{\Omega} [\mathbf{u}_{exp}(\mathbf{x}) - \mathbf{u}_{mod}(\mathbf{x}, \mathbf{p})]^2 d\Omega \quad (4)$$

3.2.2 Digital Image Correlation (DIC)

Once an image can be interpreted as a spatial discretization of light intensity, a mesh of finite elements can be used to map the values of light intensity and from the comparison of a reference photograph with another one in a deformed state it can be obtained the displacement fields between the photographs. The DIC technique is based on the principle of optical flow continuity. Each element of the mesh has the information of the mean value of light intensity of the pixels inside. So, when the the reference photograph elements provide values of light intensity, in the analysis of the deformed state photograph, the mesh deforms itself in order to preserve the light intensity of each element. In this paper, the software of DIC used was the Correli 3.0 (implemented in Matlab®). This software was developed by Hild e Roux in the Laboratoire de Mécanique et Technologie (LMT) in Cachan [13].

3.2.3 Analytical models

For the diametrical compression tests the analytical solutions for the horizontal (u) and vertical (v) displacement fields are given by:

$$\begin{aligned} u(x, y) &= -\frac{2P}{\pi t E} \left[\frac{1-\nu}{2} c - \frac{1+\nu}{2} d - \frac{(1-\nu)x}{2R} \right] \\ v(x, y) &= -\frac{2P}{\pi t E} \left[\frac{1}{2} \ln \left(\frac{b}{a} \right) - \frac{1+\nu}{2} \left(\frac{x^2}{a} \right) + \frac{1+\nu}{2} \left(\frac{x^2}{b} \right) - \frac{(1-\nu)y}{2R} \right] \end{aligned} \quad (5)$$

where x and y are the cartesian coordinates, P is the load over the sample, R is the sample radius and the terms a , b , c and d expressed as:

$$\begin{aligned}
 a &= x^2 + (R - y)^2 \\
 b &= x^2 + (R + y)^2 \\
 c &= \tan^{-1} \left(\frac{x}{R - y} \right) + \tan^{-1} \left(\frac{x}{R + y} \right) \\
 d &= \frac{(R - y)x}{a} + \frac{(R + y)x}{b}
 \end{aligned} \tag{6}$$

For the CTE (α) identification the analytical solution used is given by:

$$\begin{aligned}
 u(x, y) &= (x - x_c) \alpha \Delta T \cos \theta - (y - y_c) \alpha \Delta T \sin \theta + u_0 \\
 v(x, y) &= (x - x_c) \alpha \Delta T \sin \theta + (y - y_c) \alpha \Delta T \cos \theta + v_0
 \end{aligned} \tag{7}$$

being u and v the horizontal and vertical displacements, x and y the coordinate where the displacement is being calculated, x_c and y_c the coordinates of the center of the disc, u_0 and v_0 the horizontal and vertical rigid body displacement and θ the rigid body rotation angle.

4. RESULTS

4.1 Mechanical and thermomechanical properties

The results of the properties identified of the model composite's phases are presented in Table 1 with the respective temperatures of the tests conducted to their identification.

Table 1 – Materials properties obtained using the identification procedure by the comparison between analytical model prediction and experimental measurements from DIC.

| Temperature | 25 °C | 25 °C | 25 °C | 40-300 °C |
|----------------|-------|-----------|------------|--|
| Parameter | ν | E | σ_f | α |
| | - | [GPa] | [MPa] | ($\times 10^{-6}$) [°C ⁻¹] |
| Brass | 0.31 | 85.6 | - | 20.6 - 44.8 |
| Alumina mortar | 0.15 | 2.3 - 3.4 | 1.3 | 4.32 - 28.7 |

σ_f : fracture strength.

4.2 Model material submitted to a temperature variation

For the evaluation of the crack initiation as a function of the temperature in the sample it was analysed the maximum value of the maximum principal strain around the inclusion for each photograph taken of the model composite tested. It is possible to observe in Figure 2 that from a temperature variation of 100 °C exists a divergence of the behaviour of such parameter which is related to the crack initiation. From that temperature forward, the parameter increases as the crack propagates and gets more opened in its base.

The maximum principal strain fields from the temperature variations (a)-(d) can be seen in Figure 3. In these strain fields, it is observed at first the nucleation of four larger cracks and then, smaller ones between the larger ones. It is possible to relate the crack nucleation that can only be seen from the photograph correlation with respect to the temperature variation of 100 °C in Figure 3 with the change of inclination of the maximum value of maximum principal strain around the inclusion in Figure 2.

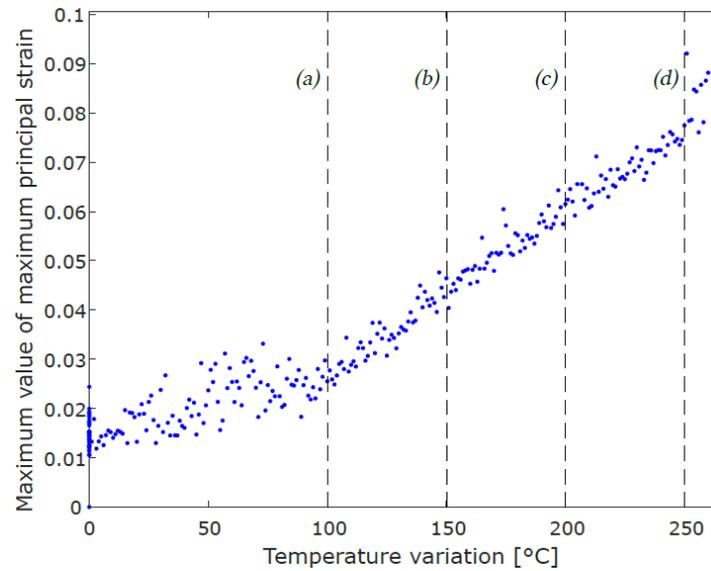


Figure 2: Maximum principal stress in the matrix inclusion interfacial region for different values of temperature variation. Temperature variations are pointed to further comparison [12].

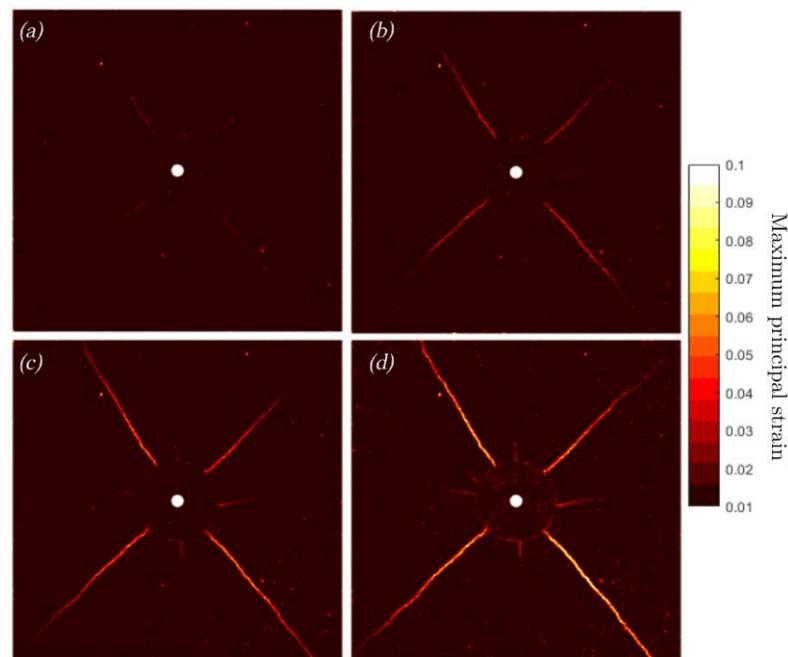


Figure 3: Evolution of the maximum principal strain field from temperature variations.

5. CONCLUSIONS

The digital image correlation technique made possible the observation of the crack nucleation and growth in a model composite submitted to a temperature variation by the use of the maximum principal stress parameter. As expected, in reason of the CTE relationship of the material's phases, radial cracks were nucleated in the matrix/inclusion interface through the matrix domain.

The evaluation of the maximum value of the maximum principal strain around the inclusion proved efficient as a parameter to evaluate the crack nucleation in the material once it is compatible with the visual DIC maximum principal strain results. As an implementation of this result, the crack growth can be monitored as a function of the temperature variance increase.

The mechanical and thermo-mechanical parameters identified do not agree the fracture stress obtained by the diametrical compression test with the one that can be calculated with the other parameters identified and the analytical formulation of the tangential stress, which demonstrate an error of identification of one or more material properties. That way, the realisation of an integrated DIC can be used to better identify the phase's properties.

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