Abstract

Digital image stereo correlation (DISC) is an optic contactless experimental technique to measure displacements and deformations. It provides full-field data with sub-pixel accuracy. It is an interesting technique to analyze local thermal properties by measuring the displacements. Furthermore, the use of a stereo camera system makes it possible to study non planar specimens. This paper presents an experimental device using DISC to measure coefficients of thermal expansion (CTE) applied to a continuous fiber composite. The experimental device was validated with well known isotropic and anisotropic materials. Then the method was applied to a non planar annular composite. Orthotropic axis were found. In addition, full-field measurements revealed an inhomogeneous response to a homogeneous loading. This method was then used to study the effect of thermal fatigue.

1 Context

Linear thermal expansion is the fractional change in length when a body is heated, or cooled, over a certain temperature range. Thermal expansion drives the dimensional behavior of a material. Designing a multi-material system, with imposed volume constraints and subject to thermal loading calls for a good control of the coefficients of thermal expansion (CTE) of each material. Thermo-mechanical behavior of fiber reinforced composites depends on the matrix composition, the fiber properties and their orientation. Different experimental techniques exist to measure thermal expansion in various environmental conditions (optical diffraction methods, dilatometer, strain gauge). However these techniques need specific sample preparation that can bring in errors (sample cutting, gauge gluing ...) and only give information at the specimen scale. With the increasing computer technology, new approaches, based on optical techniques, have been developed. Among the different full field measurement techniques the Digital image stereo correlation (DISC) method is one of the most popular. It is an optic contactless experimental technique to measure full-field displacements and strains with sub-pixel accuracy. Therefore it is an interesting technique to analyze local thermal behaviour. This technique is used to obtain mechanical and thermal properties of a wide range of materials [1–3]. Furthermore, the use of a stereo vision system makes it possible to study non planar specimens. This paper presents a new experimental method to measure thermal expansion of a complex composite using the digital image stereo correlation technique. This composite is a continuous fiber reinforced friction material used in car clutches.

2 Material and loading conditions

The material studied is the organic clutch facing that transmits the rotary motion between the engine and the wheels. It is an annular shaped continuous fiber composite constituted by a fiber glass yarn fitted with copper strips. The composite matrix is mainly composed of a phenolic thermosetting resin. The steps of the process are described in [4]. During the preforming operation, a machine guides the impregnated fibers coupling a uniform rotation with a radial translation. The two movements have different frequencies resulting in a fiber organization such as presented Fig 1. The number of sin wave per 2π phase angle (N) is an important parameter as it defines the fiber orientation [5]. The preform is put into a heated mould pressed and cured at 250°C.
The studied clutch facing has external and internal diameters of 240 and 160 mm respectively. It is 2.5 mm thick. During the engagement manoeuvre, sliding contact occurs between the clutch facing and the counter faces (flywheel or pressure plate) and the temperature of the material increases. The temperature rise can be important in the case of repetitive engagement. The thermal loading is cyclic as the clutch is engaged and disengaged many times during its life cycle.

3 Measuring CTE with DIC

3.1 Digital image Correlation

The digital image correlation (DIC) technique provides displacements and strain maps on deformed surfaces. The correlation is possible only if the surfaces have a random texture, such as a black and white speckle. The surface is often painted with black and white spray paint. A region of interest (ROI) is defined on the specimen surface. The ROI is divided into subsets. The algorithm tracks the subsets finding the corresponding location of the reference subsets in the deformed image. To compare the deformed and reference subsets, the DIC algorithm compares the grey level of each pixel in each subset. Optimized criteria for pattern matching have been formulated [6]. Here, the Zero Normalised Sum of Square Difference correlation criteria is used. Once the matching is done, the displacement components of the centre of the reference and deformed subset can be determined. The strain field is then derived from the filtered displacement field. When using one camera, (2D-DIC), the temporal correlation as described above does not take into account out of plane displacements. To determine the position of an object in the three dimensions, two simultaneous images of the same object, with a different camera angle are needed. Digital image stereo correlation (DISC or 3D-DIC) combines temporal and stereoscopic matching (Fig. 2.). The DISC method makes the difference between strain and out of plain displacements and gives access to 3D profiles.

Fig. 1. Preform and view of a clutch facing.

Fig. 2. Schematic view of the process of DISC
In order to correlate the stereo images, the correlation algorithm needs information on the orientation and position parameters of the cameras as well as the intrinsic parameters of each camera. These parameters are determined by calibrating the stereo-vision set up which is done by recording images of a calibration target. The system used in our laboratory is Vic 3D developed by Correlated Solutions [7].

3.2 Coefficient of Thermal Expansion (CTE)
The coefficient of thermal expansion describes material behaviour under thermal loading. It is defined, in its' simplest form, as the fractional increase in length per unit rise temperature (coefficient of linear thermal expansion). In the case of small deformation, the fractional increase in length is equivalent to the strain (ε), and the CTE can be expressed as follows (eq. 1)

\[ \text{CTE} = \frac{\varepsilon}{\Delta T} \]  

The CTE is defined in its linear form over a limited temperature range. For certain materials and a larger temperature range, it depends on temperature. Here, the studied temperature range is 30°C to 300°C.

4 Experimental set up and procedure
4.1 Experimental set up
Thermal testing was carried out using a climate chamber developed by France Etuves. To have an optical access to the specimen, the climate chamber is equipped with a window on top. The image capturing system consists of two CCD cameras (AVT Pike F-421B) with the resolution 2048 x 2048 pixels providing monochromatic images with 14 bit dynamic range. The software used in this study converts the 14 bit images to 8 bit (256 grey levels). The cameras field of view is 250x250 mm. Therefore 1 pixel on the CCD sensor corresponds to 0.12 mm square on the specimen. To illuminate the sample and to limit reflections, the white lights are inside the climate chamber. Two thermocouples are fixed on the rear side of the specimen and in the climate chamber respectively. The outline of the device is shown in Fig. 3. During the calibration procedure, the calibration target is placed inside the chamber so that the cameras view through the window. During calibration, distortion in the optical path is calculated and taken into account in the algorithm [8]. Thus, considering it is clean, the window of the climate chamber has limited impact on the measures.

Fig. 3.a. Outline of the experimental device, b. View of the experimental set up
Resolution and spatial resolution

Resolution and spatial resolution of this technique depend on the characteristics of the cameras and the quality of the camera setup. They also depend on the choices made for the post-processing parameters in particular the subset size [9]. When processing the data the subset size was optimized by means of the grey level entropy of the speckle pattern. Spatial resolution of displacement is directly related to subset size. Strain and displacement resolution are determined on non-loaded specimens placed inside the climate chamber at ambient temperature. For a 31x31 pixels subset, the spatial resolution of displacement is 3.7 mm, displacement resolution is 8 µm and strain resolution is 0.01% strain.

4.2 Experimental procedure

The specimen is painted with aerosol black and white spray paint to create a speckle pattern with adequate contrast. Then, it is placed inside the climate chamber, with no restraints, in a horizontal position. To measure strain due to free thermal expansion, pairs of images are taken at room temperature defining the reference state of the object. Then the temperature is increased progressively. Images are taken, every 50°C from 30°C to 300°C, when the specimen temperature is stabilized. In order to reduce the impact of noise, ten pairs of images are averaged for each temperature. These images were analysed with the DISC software Vic 3D.

5 Experiment

5.1 Experimental validation

Validity tested on isotropic materials

In order to verify the validity of the proposed technique, free thermal expansion of pure Aluminum (A5) and Aluminum Oxide (Al₂O₃) specimens were measured. The procedure is the same as described in part 4.2. For the DISC analysis of the data, a square region of interest (ROI) was selected in the middle of the specimen. This zone delimits the area over which the displacements are measured. The subset size was 33x33 pixels and 41x41 pixels for the A5 and Al₂O₃ specimens respectively. The purpose of testing the latter was to check if, considering the strain resolution, this method was able to accurately measure a small CTE. Mean values of the strains obtained for the two specimens are compared to the results from the corresponding Handbooks and presented in Fig. 4. The strain measurements of Al₂O₃ specimen are more affected by errors as the mean strains are closer to strain resolution. In each case, deformation fields were homogeneous and show good agreement with CTE reported in literature [10], [11].

Validity tested on anisotropic materials

This experimental device was developed to measure thermal expansion of anisotropic materials such as continuous fiber composites. The software Vic3D gives, for each calculated point, a 2x2 matrix
with normal and shear strains. The principal strains and principal directions can therefore be deduced locally by diagonalising these local strain tensors (eq.2).

$$
\begin{pmatrix}
\varepsilon_1 & 0 \\
0 & \varepsilon_2
\end{pmatrix}
(U_1, U_2)
= T_p^{-1}
\begin{pmatrix}
\varepsilon_{xx} & \varepsilon_{xy} \\
\varepsilon_{xy} & \varepsilon_{yy}
\end{pmatrix}
(X,Y)
T_p
(2)
$$

with $T_p = (U_1, U_2)$, $U_i = (U_{i1}, U_{i2})$, $i=1,2$

In this case $\varepsilon_1$ and $\varepsilon_2$ are the principal strains and $U_1$, $U_2$ the principal strain directions. The convention $\varepsilon_1 > \varepsilon_2$ was chosen. In the case of orthotropic materials, $U_1$ and $U_2$ are the in plane orthotropic axes. In order to verify the effectiveness of this approach, free thermal expansion of uni-directional (UD) carbon fiber reinforced bismaleimide was measured. Classic UD principal directions were found (Fig. 5).

**5.2 CTE determination of the friction material**

The device was validated on known isotropic and anisotropic materials. The same procedure was used to measure the coefficient of thermal expansion of the continuous fiber annular shaped composite described previously (part 2.). A view of the clutch facing with the subset grid numerically superimposed on the disc is shown Fig. 6. The subset size was 31x31 pixels and the step was 7. The DISC software VIC 3D was used to compute the Lagrange strain tensor. The strains were derived from the filtered displacement field with a filter box size of 15 calculated points. The principal strains are deduced as explained in part 3.1. The principal strain map ($\varepsilon_1$) for a thermal loading $\Delta T=220°C$ is shown Fig. 7. Each calculated strain maps contains 260 independent measured points. The full field data of $\varepsilon_1$ revealed that the thermal expansion in that direction is not homogeneous and depends on the distance to the centre of the disc. The expansion of the disc is greater on the edges (inside and outside diameter) than in the middle of the annular composite. This is essentially due to the fiber organization (Fig. 1).

To estimate the global CTE, the strain maps were averaged. Fig 7 presents the principal strains versus temperature.

Fig. 5. Free thermal expansion of a UD carbon fiber reinforced bismaleimide composite.

Fig. 6. View of the clutch facing and the ROI
Fig. 7. 2D view of the organic clutch facing under thermal loading ($\Delta T=220^\circ$C)

Fig. 8. Normed principal strain $\varepsilon_1$ and $\varepsilon_2$ due to free thermal expansion

The two principal strains are significantly different attesting of an anisotropic behaviour. To visualize orthotropic directions, the angle between the principal strain direction (eigenvector linked to the principal strain $\varepsilon_1$, chosen as the higher eigenvalue) and the unit vector in the radial direction was calculated (Fig. 9.). The orientation of the principal strain $\varepsilon_1$ is predominantly radial. The two in plane orthotropic directions of the composite are the radial and tangential direction of the annular disk. Two CTE are determined: a radial and a tangential CTE. In some areas radial strain is smaller than tangential strain (angle between $U_1$ and $U_r$ is $90^\circ$). This could be caused by initial inhomogeneities in the material (fiber distribution, difference in porosity concentration, initial defect).

6 Thermal Fatigue

6.1 Loading conditions

To study the effect of thermal fatigue on the dimensional behavior of the composite, the following thermal cycle was repeated (Fig. 10). The CTE was measured, with the same procedure as previously described (part 4.2), after 6, 50 and 100 cycles.
6.2 Material evolution

To determine global effect of thermal cycling, the evolution of the average CTE with the number of thermal cycles (Fig. 10.) was measured. Strain maps were used to analyze local effect of thermal cycling. As the number of cycles increases, the radial coefficient of thermal expansion decreases. The aged composite material deforms less than the as received one. Moreover, there is important scattering in the aging kinetic as shown Fig. 11. Full field strain maps show that the general decrease in CTE is partially localised. In fact, areas, where the principal strain $\varepsilon_1$ were initially minimum, expand.

Fig. 11. Evolution of the CTE with thermal cycling for 3 specimens
This is visible on the maps representing the angle between eigenvector linked to eigenvalue $\varepsilon_1$ and unit radial vector (Fig. 12. a,b,c).

To investigate the evolution of the thermal properties of the organic clutch facing, complementary tests were conducted at different stages of cycles (1, 50, 100 cycles up to 250°C): inspection by optical microscopy of composite surface and dynamic mechanical analysis (DMA).

**Optical analysis of the composite surface**

After 100 cycles, cracks up to 2.5 mm are observed on the surface of the composite material (Fig. 12). These cracks mainly ran along fiber bundle/matrix interfaces as shown Fig 12. Indeed, the difference in thermal expansion of the glass fibers (around $5\times10^{-6}$ °C) and the phenolic resin (around $10\times10^{-6}$ °C), causes thermal stress in the composite when the temperature changes. If the thermal loading is cyclic, it creates thermal fatigue and causes damage in the material.

**Dynamic Mechanical Analysis (DMA)**

The DMA tests were conducted on a 50N 0.1dB Metravib test machine. Several specimens were cut into the disk (size 40x12x2 mm). The results for a traction/compression dynamic test (1Hz, displacement +/- 5µm) are shown Fig 12. The temperature range explored is -100°C to 300°C. The temperature of the loss factor peak increases with the number of cycles. The rise may be caused by either solvent release and/or additional cross linking formation with thermal aging. In fact, studies have shown that around 250°C, condensation reactions could happen in phenol-formaldehyde type resins creating additional cross links [12], [13]. For this purpose, chemical analyses are in progress. The progressive modification of the matrix as well as the occurrence of micro-cracking with thermal fatigue could be responsible of the observed thermal behaviour of the material.

**Fig. 13. A 2 mm crack after 100 cycles**

**Fig. 14. Evolution of the loss factor with temperature, effect of thermal cycling**
Conclusion

The experimental set up described in this paper was validated and then used to determine thermal behaviour of a complex continuous fiber composite. This technique makes it possible to measure thermal behaviour of a complete structure, preserving the material integrity. The measures were used to determine orthotropic directions and CTE maps with a good spatial and strain resolution (3.7 mm and 0.01% respectively). Full field measurements also enabled detection of inhomogenities due to structure or initial defects.

Reference


