Local Strain and Damage Measurements on a Composite with Digital Image Correlation and Acoustic Emission

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LOCAL STRAIN AND DAMAGE MEASUREMENTS ON A COMPOSITE WITH DIGITAL IMAGE CORRELATION AND ACOUSTIC EMISSION

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ABSTRACT

Certain material have a non linear stress-strain behaviour under monotonic loading. This non linearity can be caused by continuous damage. To highlight this phenomena simultaneous strain and damage measurements should be taken. When working with inhomogeneous or anisotropic materials, such as continuous fibre composites, local information is essential. On the one hand, full field strain data can be obtained with Digital Image Correlation (DIC). On the other hand Acoustic Emission (AE) recording is a method that can be used for damage monitoring and location if, at least two sensors are placed on the specimen under loading. The aim of this work is to combine these two techniques to correlate strain measurements and damage location on a complex composite material during a monotonic tensile test. This composite is a continuous fibre reinforced friction material used in car clutches. These measures were used to understand the non linearity of the stress-strain curve of the as received material as well as detect volume damage after thermal cycling.

KEYWORDS : *Digital Image Correlation,Acoustic Emission, Location, Composite Material*

1 CONTEXT

To predict the behaviour of a structure, a good knowledge of the constitutive relations of each part is essential. To obtain the stress/strain relations strain measurements are conducted on simple mechanical tests. For certain materials, the stress-strain curve may be non linear. Damage is one of the causes of non linearity in the stress/strain curve. To identify such a behaviour strain and damage must be measured simultaneously. To measure strain many techniques can be used (extensometers, strain gauges, ..), however, when working with inhomogeneous or anisotropic materials, such as continuous fibre composites, accurate strain measurements call for full field data. Amongst the different full field measurement techniques, Digital Image Correlation (DIC) is one of the most popular [1]. It is an optic contactless experimental technique to measure full field displacements and strains with sub-pixel accuracy. Failure mechanisms can be identified with different non destructive techniques such as Acoustic Emission (AE) recording which can be used for damage monitoring. In fact elastic waves are emitted as a consequence of crack initiation and propagation. Therefore analysing the acoustic activity gives information on the type of damage that occurs in the material. Furthermore, if at least two sensors are placed on the specimen under loading, and the wave propagation velocity is known, location of each acoustic event is possible.
The aim of this work is to combine these two techniques to correlate strain measurements and damage location during a monotonic tensile test and determine if the non-linearity of the stress-strain curve is due to volume damage. In addition, as car clutches are submitted to thermal cycling, volume damage was characterised on thermally cycled specimens by using AE signals emitted during a monotonic tensile test.

2 MATERIAL AND LOADING

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 fibre composite constituted by a fibre glass yarn fitted with copper strips. The studied clutch facing has external and internal diameters of 240 and 160 mm respectively. The composite matrix is mainly composed of a phenolic thermosetting resin. The steps of the process of fabrication are described in [2]. During the preforming operation, a machine guides the impregnated fibres coupling a uniform rotation with a radial translation. The two movements have different frequencies resulting in a fibre organisation such as presented figure 1. The number of sin wave per 2π phase angle (N) is an important parameter as it defines the fibre orientation [3]. The preform is put into a heated mould pressed and cured at 250°C. The fibre organisation confers an orthotropic behaviour to the material. The orthotropic axes are the radial and the tangential axes [4]. In this paper only mechanical properties in the tangential direction were studied. Rectangular specimens (20x120) were cut into the disc to perform the tensile tests as shown figure 1.

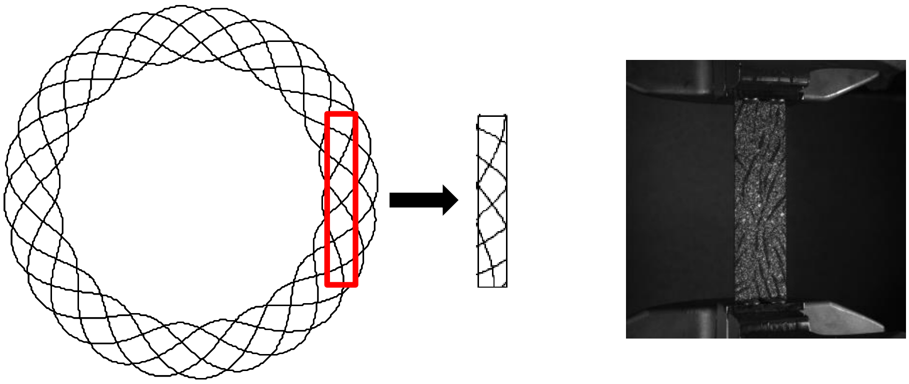

Figure 1 : Preform and view of the rectangular specimen cut into the disc.

3 EXPERIMENTAL TECHNIQUES

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 surface has 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

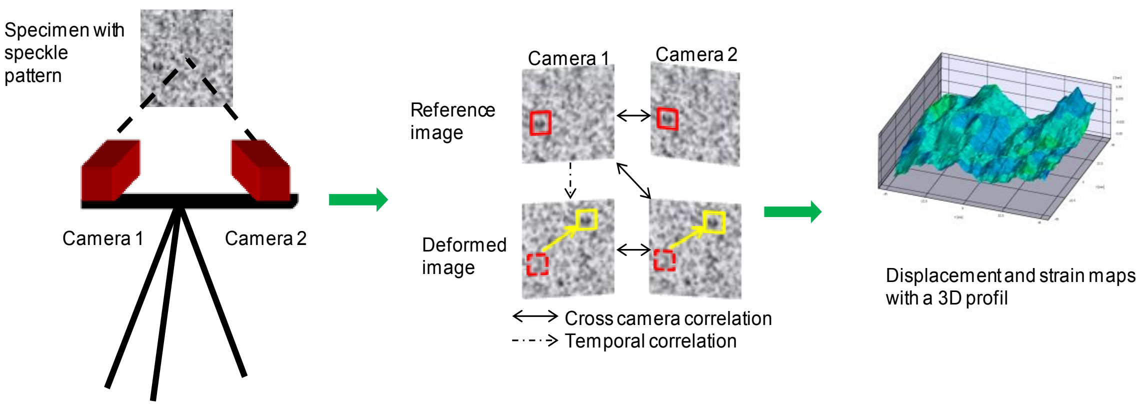

Figure 2 : Schematic view of the process of DISC

(ROI) is defined on the specimen surface. The ROI is divided into subsets which are tracked by the algorithm which finds the corresponding location of the reference subsets in the deformed image. To compare the deformed and reference subsets, the DIC algorithm compares the gray level of each pixel in each subset. 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 (Figure 2). The DISC method makes the difference between strain and out of plain displacements and gives access to 3D profiles. 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 [5].

3.2 Acoustic emission : accuracy of location

Acoustic emission (AE) signals were acquired and processed with the AE acquisition and analysing system AEwin for Mistras of Physical Acoustics Corp. The AE signals during the tests were detected by two piezoelectric sensors (type R15) attached to the sample by a silicon grease and clips. The threshold of the AE system was set to 35dB, any event with a lower amplitude was not detected. To test the accuracy of the AE system when locating events, 100 dB events were generated on a marked specimen. The AE location map was then compared to the known location of the events. Two sources of errors have been identified : the velocity uncertainty and the repeatability of the acquisition system. The wave velocity of our specimens is 2 770 +/- 140 m/s . Here, this uncertainty corresponds to a variability in the location of +/- 1 mm. The repeatability was also tested and that gave an uncertainty of +/- 1.9 mm. These two tests give an overall confidence interval of 5 mm on the location accuracy of our system.

3.3 Experimental set up

Specimens were cut into the annular disc in the tangential direction. The dimensions of the loaded area were 20x80 mm. The tensile loading was performed at an imposed displacement rate of 1mm/min until the complete failure of the specimen. During the test the load, the strain field and the acoustic emissions signals were recorded. The two sensors were placed at each end of the specimen, 70mm from each other. The wave velocity was measured for each specimen prior to testing. The outline of the experimental set up is shown Figure 3.

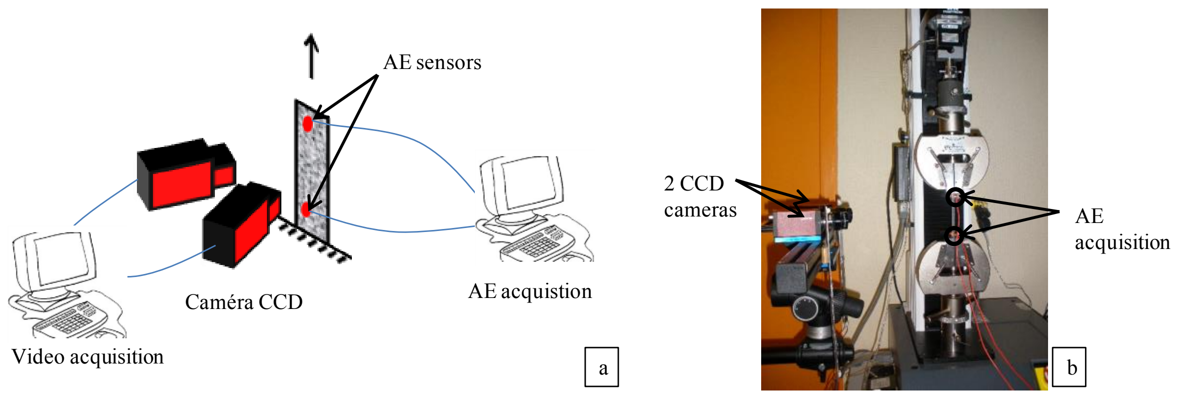

Figure 3 : Outline of the experimental set up (a) and photo (b)

4 RESULTS

4.1 Acoustic emission signals versus load

AE signals are detected very early in the test under 10% of the maximum load. In the first phase (1), up to 60% of the maximum stress, many events of small amplitude and low energy occur (figure 4.a). These events are often related to matrix cracking [6]. In this phase the AE emission rate increases drastically (figure 4.b). In the second phase events over 80 dB and high energy are measured. These events are linked to fibre break. Over a load of 60% the AE rate is constant and around 100 events per second. Low amplitude and low to average energy events still occur in this phase. These two aspects combined could indicate friction due to fibre/matrix debonding. This change in damage mechanisms is not visible on the stress curve. The third phase is when failure occurs : multiple high energy and high amplitude events indicate multiple fibre breakage. In the same time, numerous events of lower amplitude are a sign of important matrix cracking. In this phase the material fails.

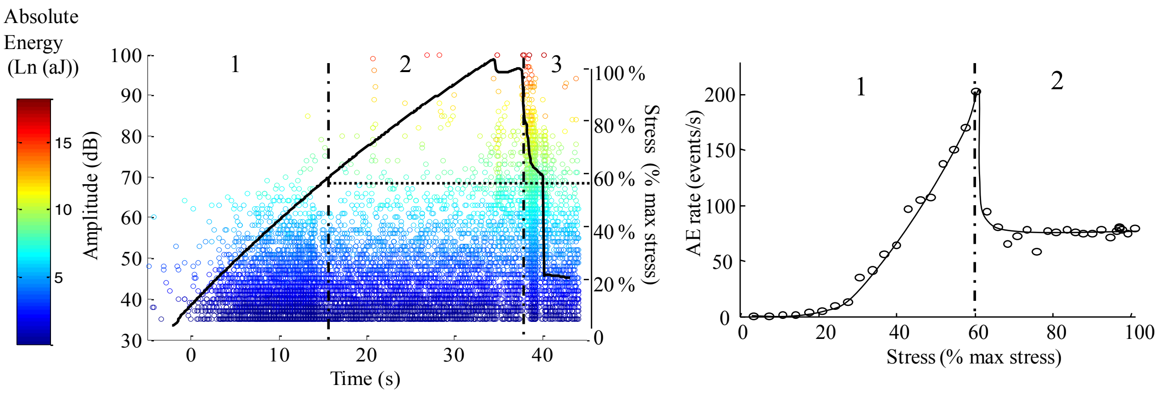

Figure 4 : (a. left) Amplitude and energy of the AE signals and stress curve. (b. right) AE rate versus stress

4.2 Location

The simultaneous DIC and AE measurements give local information on strain and local damage. The outline and the photo presented on figure 5 show the relative position of the two AE sensors and the region of interest (ROI) where the strain field was measured.

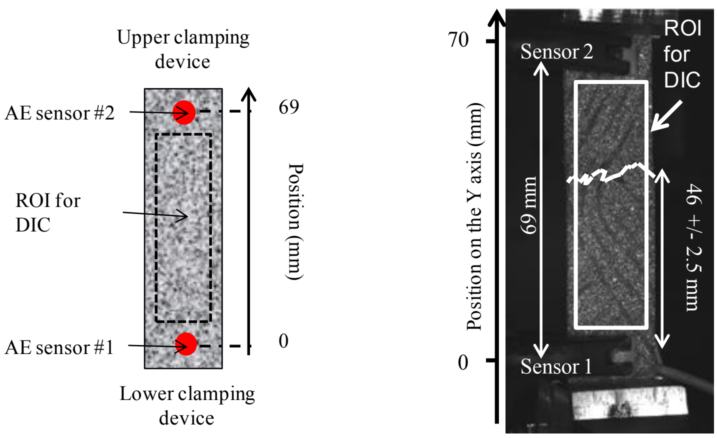

Figure 5 : Position of the two AE sensors and the region of interest (ROI)

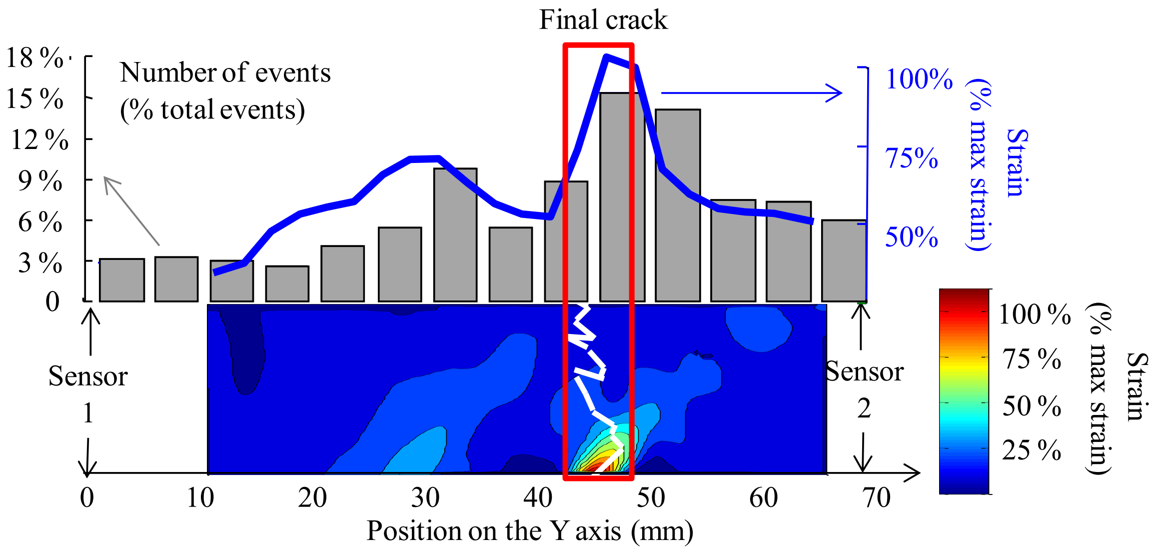

Figure 6 : Cumulative number of acoustic events and strain field prior to failure.

The load was applied in the Y direction. The strain field before failure and the cumulative AE events are shown figure 6. To match the coordinate system of the acoustic emission location and the strain field, the coordinates of the crack were used : the maximum strain was matched with the crack location. The same repositioning was applied to the AE histogram : the maximum number of hits was matched with the crack coordinates. Considering the location accuracy and the repositioning of each coordinate system, the AE events were counted on 5 mm strips, every 5 millimetres (no overlap). On the AE event histogram (top of figure 6) a higher number of events occur around 30-35 mm and 40-50 mm. These two regions correspond to two high strain areas in the strain field. These high strain zones are in fact strips oriented at around 45° from the loading axis. The fibre organisation in the specimen is complex as shown on figure 1. However a previous study [4] revealed that the rectangular specimen had meshes in the 45° direction which could explain the aspect of the strain field.

5 EFFECT OF THERMAL CYCLING

During the engagement manoeuvre, sliding contact occurs between the clutch facing and the counter

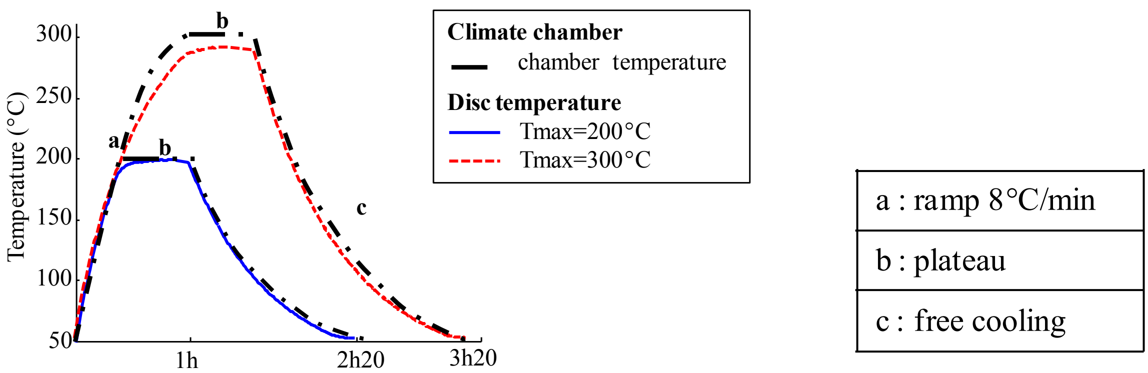

Figure 7 : Thermal cycles

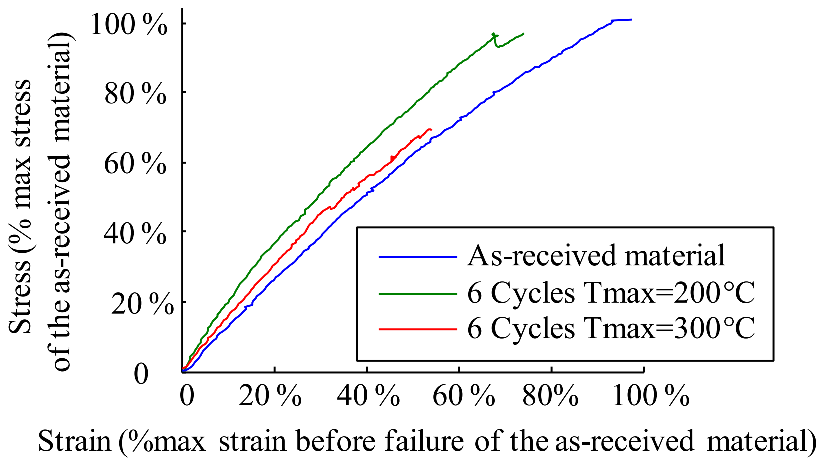

Figure 8 : Stress-strain curves for the as-received and thermally cycled material. Displacement rate 1mm/min

faces (flywheel or pressure plate) which increases the material temperature. 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. Thermal cycling can cause volume damage and a good knowledge of these phenomena are necessary to guarantee life expandency. To identify and quantify this degradation mechanism, specimens were submitted to 6 thermal cycles, described in figure 7, with a maximum temperature of 200°C or 300°C. The specimens were then tested with the same monotonic tensile test as described in part 3.3. Strain fields and AE signals were measured. Figure 8 shows the stress-strain curves for the as-received and cycled material. The 200°C thermal cycles hardly change the ultimate strength of the material but decreases the maximum strain before failure. The 300°C cycles have a greater impact on the ultimate strength : after 6 cycles the ultimate strength is reduced by 30 %.

AE signals for the two cycled specimens are shown figure 9. The phases 1, 2 and 3 have been identified with the same criteria as part 4.1, based on the AE rate and the discontinuities of the stress curve. When cycled at 200°C the specimen has the same ultimate strength but different AE signals. The shift from phase 1 to 2 happens at half the load of the as received one (30 % max stress of the as received material). Furthermore acoustic events of high energy and high amplitude are measured for a very low load, including 100dB events. The same observations can be made for the

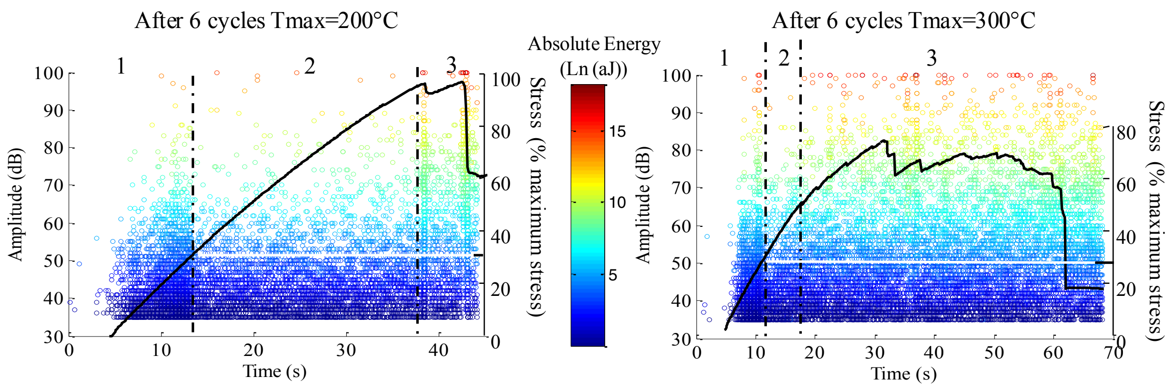

Figure 9 : Amplitude and energy of the AE signals with the stress curve of the 200°C and 300°C cycled specimens respectively.

specimen cycled at 300°C, however the second phase is shorter and the material starts failing earlier in the test, discontinuities appear on the stress curve. Fibres break when 20% of the maximum load of the as received material is reached. The AE signals have shown that damage initiation and propagation in a thermally cycled material is different from the as-received material. This evolution is a sign of damage creation and weakening of the matrix and the fibres caused by thermal cycling. Fibres are more affected by 300°C cycles.
These results give an information on the volume degradation which completes previous results on the damage mechanisms occurring on a thermally cycled clutch facing where surface cracking was observed [7]. Macroscopic cracks were found on the surface of the 300°C cycled specimens, however nothing was visible, at that scale, on the 200°C cycled. The additional information given by AE signals as a damage monitoring technique has highlighted the fact that 200°C cycled specimen are affected by thermal cycling.

6 CONCLUSIONS

The aim of this work was to have a better understanding of the non-linearity of the stress-strain curve of the composite used in car clutch facings. To answer this question, simultaneous measures of the strain field, using DIC, and damage location, using AE, were done on a rectangular specimen under monotonic tensile loading. Local strain was then compared to local damage. The correlation between strain fields and AE location is possible providing correct use of the coordinate systems. It was found that maxima in the strain field correspond to increased local AE activity. Continuous damage was recorded during the test which could explain the non-linearity of the stress-strain curve. Furthermore AE signals were use to detect volume damage on specimens that were thermally cycled at 200°C or 300°C. After 6 cycles, the specimens were tested under monotonic tensile load with AE sensors detecting AE signals. These measures revealed volume damage of the 200°C cycled specimens that was neither visible on the stress-strain curve nor on the surface of the specimen.

7 REFERENCES

[1] M. A. Sutton, J. J. Orteu, and H. W. Shreier, *Image Correlation for Shape Motion and Deformation Measurements. Basic Concepts, Theory and Application*, 1st Editio. Springer US, 2009.

[2] M. Bezzazi and A. Khamlichi, “Experimental characterization of frictional behaviour of clutch facings using Pin-on-disk machine,” *Mater. Des.*, vol. 28, pp. 2148–2153, 2007.

[3] Z. H. Karadeniz and D. Kumlutas, “A numerical study on the coefficients of thermal expansion of fiber reinforced composite materials,” *Compos. strucutres*, vol. 78, pp. 1–10, 2007.

[4] C. Flament, M. Salvia, B. Berthel, and G. Crosland, “Digital image correlation applied to thermal expansion of composites,” in *ICCM*, 2013, pp. 5235–5243.

[5] “Correlated Solutions.Inc.” [Online]. Available: http://www.correlatedsolutions.com/.

[6] O. Ceysson, “Caracterisation du comportement en fluage de materiaux compoistes carbone/epoxyde étude de l’endommagement,” 1996.

[7] C. Flament, M. Salvia, B. Berthel, and G. Crosland, “Effect of thermal cycling on the mechanical properties of a continuous fibre composite used for car clutch facings,” in *Fatigue 2014*, 2014, pp. 42–47.