

## RESIDUAL STRESS ASSESSEMENT USING OPTICAL TECHNIQUES

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### SYNOPSIS

The goal of this work is the development of different experimental techniques to measure residual stresses as alternative to the hole-drilling method with strain gages. The proposed experimental techniques are based on the use of Moiré Interferometry and in-plane Digital Speckle Pattern Interferometry (ESPI). They are field techniques that allow measure in-plane displacements without contact and with high resolution. Grating replication techniques are developed to record high quality diffraction gratings onto the specimen's surfaces. It is also, developed an optical assembly of laser interferometry used to generate the master grating (virtual). It was designed and implemented an in-plane interferometer to measure displacements in one direction. It was also developed a drilling equipment to provoke the stress relaxation in the specimens. During residual stresses measurements the obtained fringe patterns (Moiré and speckle) are video recorded. Image processing techniques are used to assess the in-plane strain field. A finite elements code (ANSYS®) is used to simulate the process of relaxation of stresses whose values will be compared with the experimental ones and to calculate the hole-drilling calibration constants.

### INTRODUCTION

A new process to measure residual stresses with two optical techniques (in-plane ESPI and Moiré Interferometry) was developed and combined with the hole-drilling method in a ring and plug specimen. Before doing the test it is necessary to obtain the calibration coefficients. In order to compute these coefficients a numerical simulation was developed (FEM), using the ANSYS® programme.

To prepare the specimen an aluminium ring and plug with 0.05 mm of diametrical interference between those was used. The first test was prepared with in-plane ESPI technique. Holes with different diameters and depths were drilled. An image processing software package was developed by LOME (Laboratory of Optics and Experimental Mechanics) to treat the images and obtained the displacement field. The second test was done with Moiré Interferometry technique, after replication of a grating with 1200 l/mm on the specimen surface and was prepared a set up to measure the displacement field in two directions; a few holes were drilled in different radial distances from the centre of the specimen.

## RESIDUAL STRESS MEASUREMENT SYSTEM

In the current work a Moiré Interferometry (Post, 1997) and double-illumination-beam phase-shifting ESPI (Jones, 1974) systems were developed to measure the residual stress. The system's software and related algorithms transform surface displacement measurements into residual stress values.

Two different system configurations were used, one for each technique. This is possible to see schematically in figure 1.

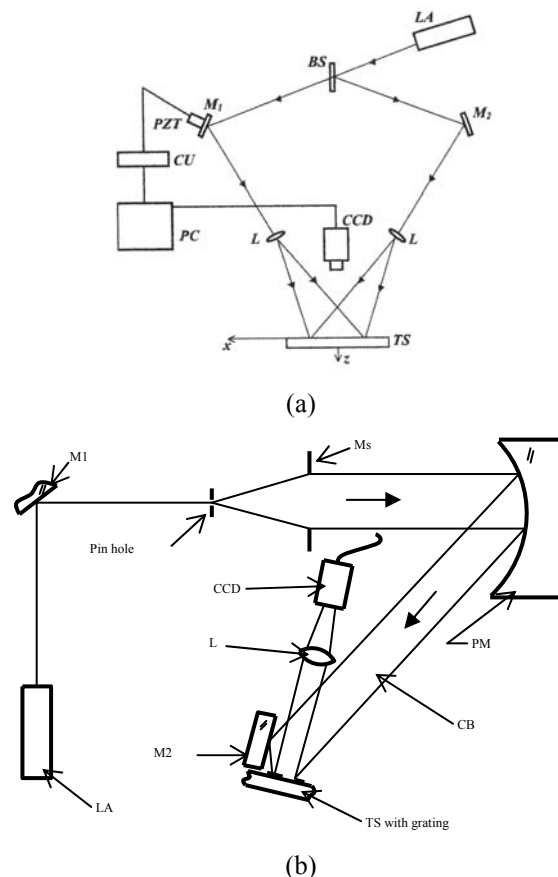


Fig.1 Scheme of optical systems configurations: (a) ESPI to measure in plane (Jones, 1974); (b) Moiré Interferometry (Ribeiro, 2005).

Where LA is a laser, BS is a beam splitter, M1 and M2 are plane mirrors, PZT is a piezoelectric, L is a lens, TS is the test specimen, Ms is a mask, CB is the collimated beam, PM is a parabolic mirror.

The principles of residual stress measurements with these techniques associated with the hole drilling method are the same that are used in the conventional method with strain gages. Drilling a hole on the surface of a specimen with residual produces a residual stresses relaxation around the hole. An optical technique was used to measure the residual stresses relaxation instead of strain gages that are commonly used in conventional method.

The stress analysis algorithms are based on the work of Nelson (Nelson et al, 1997) and Wu (Wu et al, 1998), but have been well adapted to work with an ESPI and Moiré Interferometry system. For the ESPI an initial interferogram is acquired and saved. Then, the drill is placed in front of the test specimen and a small hole is drilled to a given depth. Next the drill is

removed and another interferogram is acquired. These interferograms provide the change in the illumination beam's path length,  $\Delta P$ , which corresponds to the surface displacements caused by the stress relaxation. For the Moiré Interferometry system, it consists in applying a grating on the surface of the specimen, drilling a hole at the desired place, which is followed by recording of the relaxed Moiré fringes, and finally the residual stress field is computed by means of appropriate stress–displacement relationships obtained by FEM.

The displacements caused by the relaxation of residual stresses are related between themselves through the following equations,

$$u_r^k = \begin{bmatrix} A + B \cos 2\theta_k \\ A - B \cos 2\theta_k \\ 2B \sin 2\theta_k \end{bmatrix}^{-1} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} \quad (1a)$$

$$u_\theta^k = \begin{bmatrix} C \sin 2\theta_k \\ -C \sin 2\theta_k \\ 2C \cos 2\theta_k \end{bmatrix}^{-1} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} \quad (1b)$$

Where  $u_r^k$  and  $u_\theta^k$  are, respectively, the radial and tangential displacements;  $k = 1, 2, 3$ ,  $k$  are the number of measured points;  $A$ ,  $B$  e  $C$  are coefficients that depend on the elastic constants, the hole dimensions (diameter and depth) and the radial position around the blind hole;  $\theta_k$  is the cylindrical coordinate of the measurement point,  $\sigma_{xx}$ ,  $\sigma_{yy}$  and  $\tau_{xy}$  are stress components in Cartesian coordinates.

## NUMERICAL DETERMINATION OF CALIBRATION COEFFICIENTS

For the numerical determination of calibration coefficients (Lu, 1996 and Schager, 1981) that were used on the hole-drilling method, a three-dimensional finite element model was used. This study was developed with brick, homogeneous and isotropic elements. ANSYS three-dimensional finite element model, with 5525 parametric brick elements (SOLID185) with 8 nodes were used as represented in figure 2 (Ribeiro, 2005).

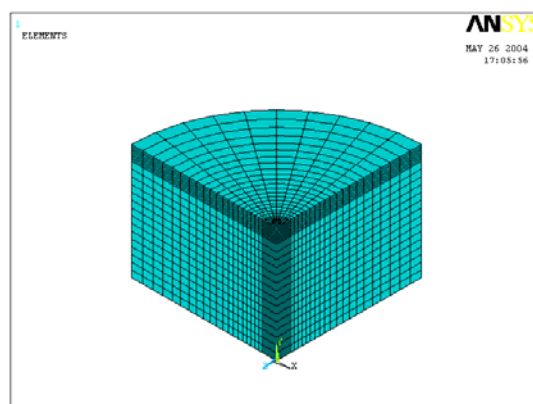


Fig.2 Meshing of three-dimensional model.

The material and geometric parameters used in this analysis are represented in table 1.

Table 1 – Material, geometric and load conditions.

$\sigma$ [MPa]	$E$ [MPa]	$\nu$	$r_0$ [mm]	$h$ [mm]
100	$7.0 \times 10^4$	0.3	1.0	0.5

where  $\sigma$  is the specified residual stress,  $E$  is the elastic modulus of material,  $\nu$  is the Poisson ratio of material,  $r_0$  is the hole radius and  $h$  is the hole depth.

Two different states of residual stresses were considered.

- Equi-biaxial:  $\sigma_{xx} = \sigma_{yy} = \sigma$ ,  $\tau_{xy} = 0$ , the correspondent stresses in cylindrical coordinates are:  $\sigma_{rr} = \sigma_{\theta\theta} = \sigma$ ,  $\tau_{r\theta} = 0$ . This drilling condition is equivalent to uniform pressure on the surface of hole. It is represented on the left side of figure 3 (a).
- Pure shear:  $\sigma_{xx} = -\sigma_{yy} = \sigma$ ,  $\tau_{xy} = 0$ , the correspondent stresses in cylindrical coordinates are:  $\sigma_{rr} = \sigma \cos 2\theta$ ,  $\sigma_{\theta\theta} = -\sigma \cos 2\theta$ ,  $\tau_{r\theta} = -\sigma \sin 2\theta$ . This drilling conditions is equivalent to a harmonic distribution of radial stresses  $\sigma_{rr} = -\sigma \cos 2\theta$  and a shear stresses  $\tau_{r\theta} = \sigma \sin 2\theta$ , both acts on the hole edge. They are represented on the right side of figure 3 (b).

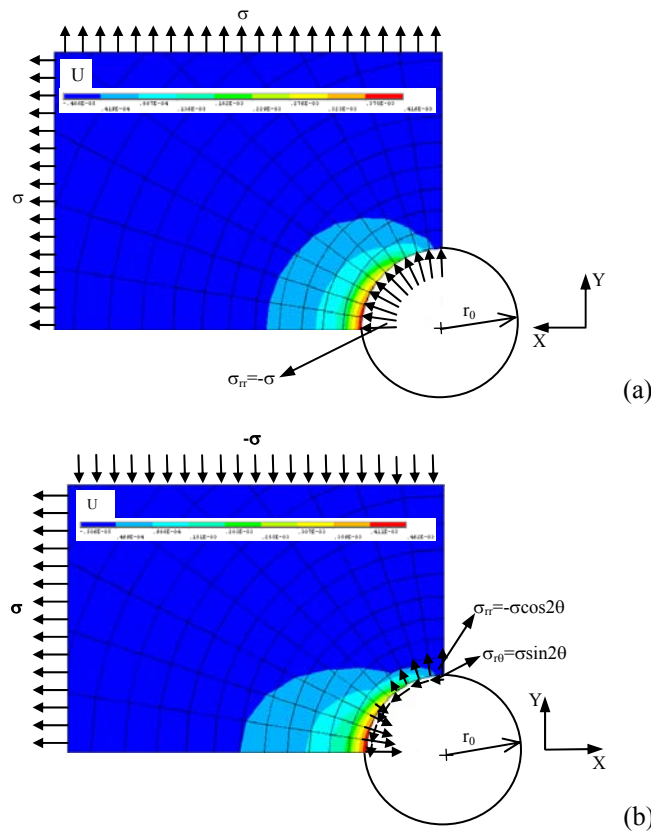


Fig.3 Three-dimensional finite elements model for determination of calibration coefficients: (a) equi-biaxial stresses –  $\sigma_{xx} = \sigma_{yy} = \sigma$ ,  $\tau_{xy} = 0$ ; (b) pure shear stresses –  $\sigma_{xx} = -\sigma_{yy} = \sigma$ ,  $\tau_{xy} = 0$ .

One way to compute the calibration coefficients is using the expressions of reference (Wu, 1998), which for the case in analysis are:

$$A\left(E, \nu, r_0, r, \frac{h}{d_0}\right) = \frac{u_r(r, \theta)}{2\sigma} \quad (2a)$$

$$B\left(E, \nu, r_0, r, \frac{h}{d_0}\right) = \frac{u_r(r, \theta)}{2\sigma \cos 2\theta} \quad (2b)$$

$$C\left(E, \nu, r_0, r, \frac{h}{d_0}\right) = \frac{u_\theta(r, \theta)}{2\sigma \sin 2\theta} \quad (2c)$$

The calibration coefficients were numerically determined for a depth of 0.5 mm, the hole diameter was considered 2 mm and the radial distance for measurement  $1.2r_0$  of the hole center. The tested specimen was made an aluminum alloy (1050). In the following table are represented the values of calibration coefficients that were numerically determinate.

Table 2 – Calibration coefficients.

A	B	C
$4.64 \times 10^{-6}$	$5.88 \times 10^{-6}$	$3.82 \times 10^{-6}$

## RING AND PLUG SPECIMEN

An aluminum shrink-fit ring and plug was chosen for this experience for different reasons. This specimen has a closed form solution for the residual stresses, and the stress distribution is relatively simple: the stress is constant in the plug, and only depends of radial position in the ring. On the other hand, this type of specimen provides the full range of biaxial stress states for testing. In the ring near the interface,  $\sigma_\theta$  is positive and  $\sigma_r$  is negative. Near the outer edge of the ring the stress state is nearly uniaxial since  $\sigma_r$  goes to zero. In the plug, the stress state is equi-biaxial,  $\sigma_\theta = \sigma_r$ . Therefore, with one specimen it is possible to demonstrate the ability of the optical system on three stress states (Steinzig, 2001).

An aluminum alloy (1050 with 90% of Al) was chosen as the material for the ring and plug. This alloy is readily available, well characterized, and has good yield strength characteristics. The Young modulus for this material is  $E=70$  GPa and the Poisson's ratio  $\nu=0.3$ .

The nominal dimensions of the specimen: exterior and interior diameter ring were, respectively, 100 mm and 50 mm; the plug diameter had 50 mm. The ring and plug specimen had a radial interference of 0.05 mm. The thickness of both elements was 13 mm.

Before de assembling two strain gages were mounted, whose centers were at same radial distance (30 mm) but measuring in two orthogonal directions (tangential and radial). These strain gages were used to precisely determine the stress state after the assembling and guarantee that the measured interference was correct.

For assembly, the plug was cooled in liquid nitrogen ( $-160$  °C) and the ring heated ( $40$  °C) which leaves approximately 0.2 mm clearance between them. Figure 4 represents the apparatus that was used in the process of assembly.

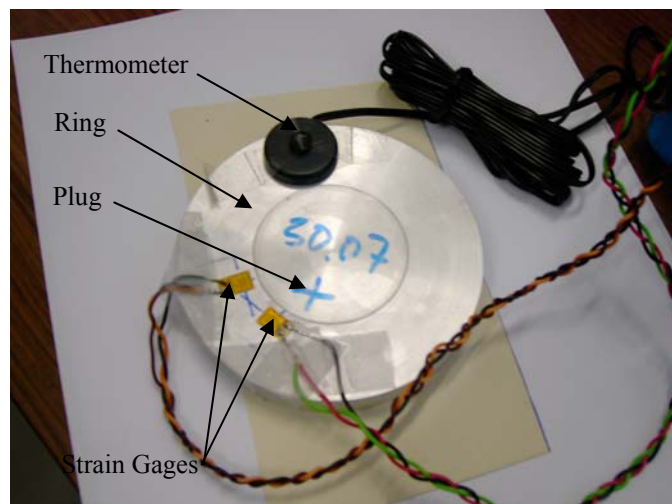


Fig.4 Apparatus used to make de assembly.

The stress state of the ring and plug can be calculated (Ugural, 2004). First the pressure was calculated by:

$$p = \frac{E\delta}{2R_i} \frac{(R_0^2 - R_i^2)}{R_0^2} \quad (3)$$

which is taken as positive, and  $\delta$  is the radial interference between the ring and plug. In the plug the stress are equal to the pressure in the radial and angular directions. For the ring, the stresses are:

$$\sigma_r = \frac{pR_i^2}{R_0^2 - R_i^2} \left( 1 - \frac{R_0^2}{r^2} \right) \quad (4a)$$

$$\sigma_\theta = \frac{pR_i^2}{R_0^2 - R_i^2} \left( 1 + \frac{R_0^2}{r^2} \right) \quad (4b)$$

For the pressure load conditions of 47.3 [MPa], the strain gages measurements give the average stresses  $\sigma_r$  and  $\sigma_\theta$ , on the strain gages grid, these values are represented on the following table

Table 3 – Average stresses  $\sigma_r$  and  $\sigma_\theta$  measured by strain gages.

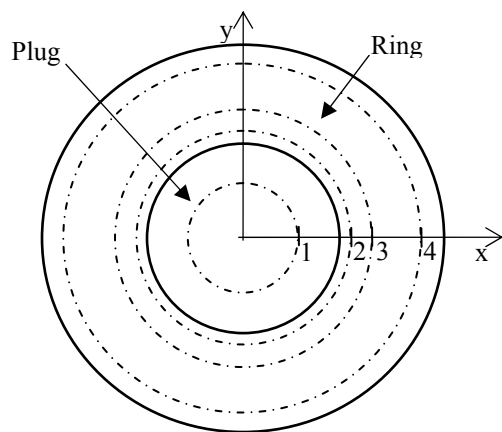
$\sigma_r$ [MPa]	$\sigma_\theta$ [MPa]
49.9	-30.3

These values are similar with the closed form solution for the center of strain gages grids.

## MEASUREMENT OF RESIDUAL STRESSES

After the preparation of the specimen and the verification of its stress state, several measurements of residual stresses were made using the hole-drilling method associated with the optical techniques for in-plane ESPI and Moiré Interferometry.

The points that were used to measure the residual stresses are represented on figure 5.



The radial distance from the center of plug:

- Point 1 – 15 mm
- Point 2 – 29 mm
- Point 3 – 32 mm
- Point 4 – 45 mm

Fig.5 Diametrical location of measurement points.

The residual stress was measured in all these points with in-plane ESPI, without any material influence, because they were positioned in different angular conditions. However, with Moiré Interferometry it wasn't possible to measure the points located in different angular positions, the grating was fixed only on a small part of the specimen, and to avoid any influence of stress relaxation around the drilling hole the measurements were made in two points.

The optical set up used to measure residual stresses with in-plane ESPI and Moiré Interferometry are schematically represented on figures 1 (a) and (b), respectively. Figure 6 shows the additional system for the hole drilling.

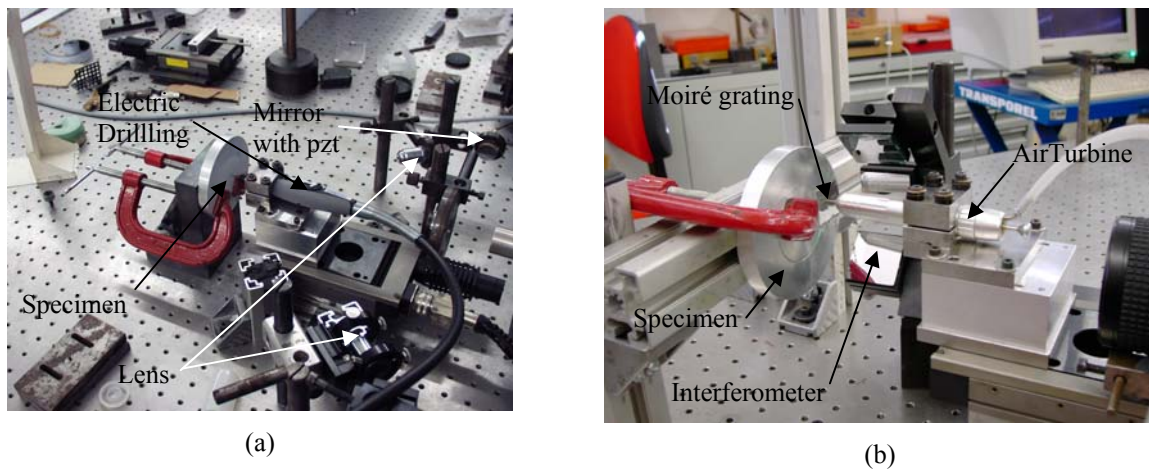


Fig.6 Apparatus to measure residual stresses using the hole-drilling technique associated to: (a) in-plane ESPI; (b) Moiré Interferometry.

## RESULTS

Eight images were necessary to use ESPI technique. Four before drilling the hole and four after that. When drilling the hole strain relaxation occurred around it and the ESPI system computes the difference between the two stages. The final image that was obtained after the holes had been drilled is presented in figure 7 (a). Figure 7 (b) represents the displacement field after image processing, which includes, phase filtering, phase unwrapping and pseudo color representation.

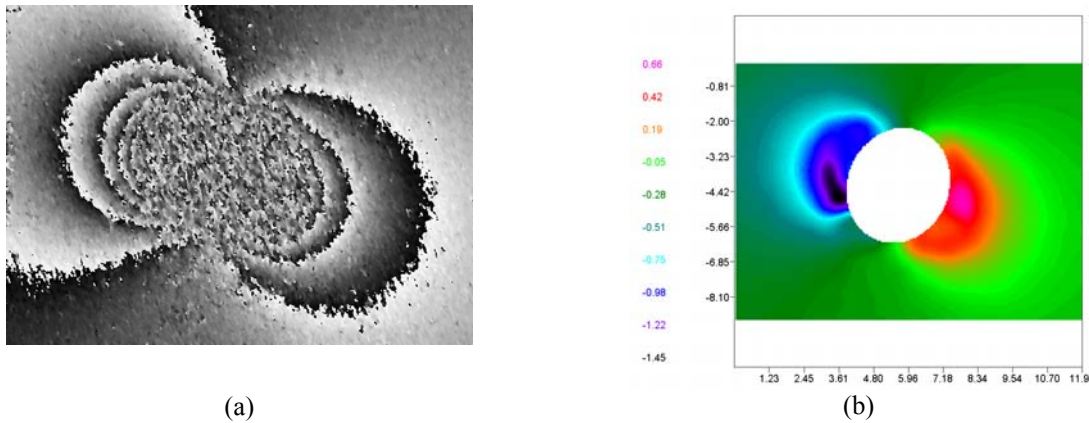


Fig.7 (a) Phase map of displacement field (b) Unwrapped phase map.

The results obtained after drilling a few holes in the specimen are represented in the figure 8.

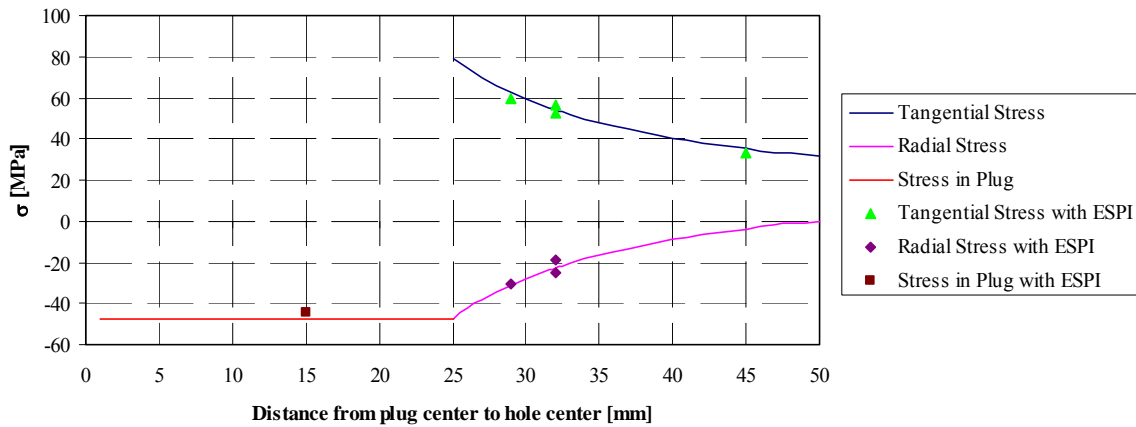


Fig.8 Closed form solution and experimental measurements with ESPI.

For the Moiré Interferometry technique four images after drilling a hole were taken, between each image a phase shift of  $90^\circ$  using a glass plate with parallel faces is made. Based in these four images the phase map is calculated. To compute the displacement field an algorithm is used to unwrap the phase map. In figures 9 (a) and (b) it's possible to observe an example of the phase map around the hole and the computed displacement field after image processing (unwrapping).

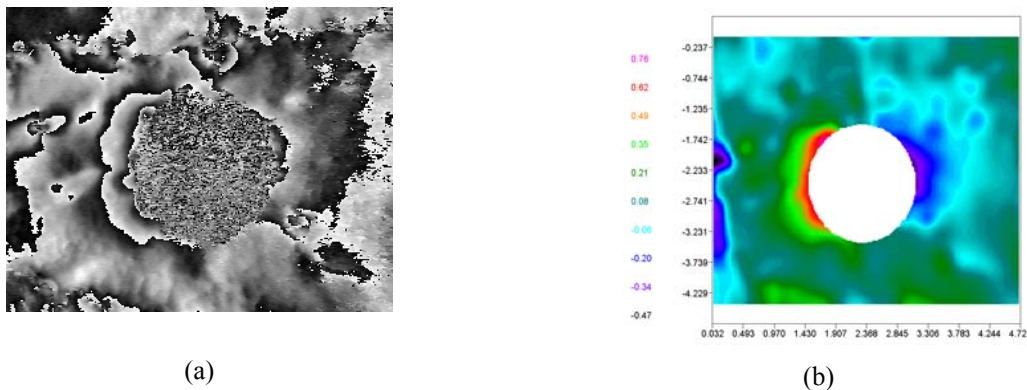


Fig. 9 (a) Phase map of displacement field (b) Unwrapped phase map.

The results obtained after drilling two holes in the specimen are represented in the figure 10.

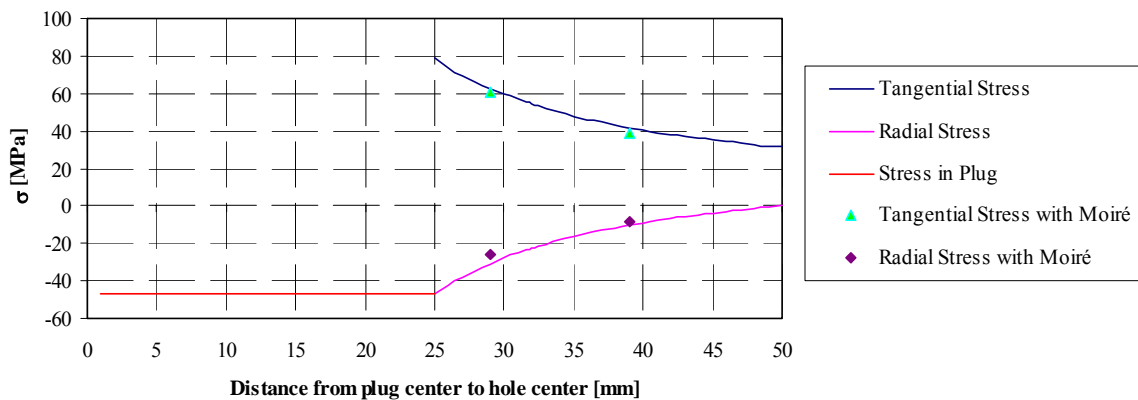


Fig. 10 Closed form solution and experimental measurements with Moiré.

## CONCLUSIONS

The experimental results that were measured with in-plane ESPI and Moiré Interferometry have a good agreement with the closed form solution. These optical techniques are a very interesting alternative to the traditional hole-drilling method with strain gages, and with other advantages, like the possibility to measure displacement fields, better sensibility and resolution. These systems quickly convert the displacement data obtained by the optical techniques (Moiré Interferometry and in-plane ESPI) to values of residual stress through a series of calibration coefficients obtained by FEM simulation.

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