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PRELIMINARY EVALUATION: THE INDENTATION METHOD COMBINED WITH A RADIAL INTERFEROMETER FOR RESIDUAL STRESS MEASUREMENT

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ABSTRACT

This paper presents a combined system based on electronic speckle pattern interferometry (ESPI) and the indentation method to determine residual stresses in ductile materials. The system allows the measurement of the radial in-plane displacement field generated when a specimen subjected to residual stresses suffers local plasticity. This novel approach for measuring residual stresses has the advantage of being nondestructive and can be easily applied to *in situ* tests. The description of the combined system is followed by the presentation of preliminary results which illustrate the ability of this new technique to identify principal residual stresses and their respective principal directions.

Keywords: *ESPI, residual stresses, nondestructive evaluation, radial interferometer, indentation, hole-drilling, electronic holography.*

1 INTRODUCTION

Residual stresses are present in many structures and mechanical components. They may be produced by fabrication operations such as casting, rolling, welding, heat-treating or forging, or may occur during the life of structures. These stresses exist without the action of external forces and they can be combined with service loads. In consequence, this resulting combination affects the mechanical behavior of structural materials and may be the reason of premature failure. Moreover, compressive residual stresses are intentionally introduced in some manufacturing processes to increase fatigue resistance and also to improve other material properties [9],[11].

The measurement of the stress and residual stresses in structures is an operation of great importance for the correct management and analysis of risks, as well as evaluating the rehabilitation and the performance of project and assembly. The evaluation of the residual stresses for analytical methods is very difficult normally demanding the knowledge of all history of the material. This information is rarely known with the necessary severity.

Some methods of measurements of residual stresses have been developed. Good part of these indirectly determines the residual stresses through the effect that the relief of the residual stresses provokes on the material. The most common is to provoke the relief of the stresses by sectioning or the hole-drilling in a flat surface. The measurement of the effect of the relief of stresses on the remaining material normally is made by means of resistance strain gauges.

For the general case in which the direction of the residual stresses is not known, a speckle interferometer with two dual-beam illumination beams must be used in order to separate measurement of both in-plane displacement components. A step forward to solve these problems was recently given by Albertazzi et al. [1],[2] with the development of a novel double illumination ESPI system to measure radial in-plane displacements. This radial interferometer was combined with the hole drilling technique to obtain a portable device which measures residual stresses outside of the optical bench. This system allows the measurement of the principal residual stresses and their direction from the analysis of only one correlation fringe pattern.

This paper presents an alternative method for residual stress evaluation. This technique is typically applied to flat surfaces, using a punctual indentation device to generate the radial displacement field. Some qualitative results are presented showing the power of this technique.

2 THE RADIAL INTERFEROMETER

The used radial interferometer is schematized in figure 2.1. This interferometer was incorporated in a portable device for measurement of residual stresses, called MTRES.

The MTRES initially was developed for measurements of residual stresses for the hole-drilling method and holography electronic [1]. It is used double illumination in order to confer for radial sensitivity measurement in-plane. With this configuration the radial component of the displacement in the surface of specimen is measured. Figure 2.1 schematizes, in cut, the pair of mirrors that guides the two fractions of the ray at point ***P***. These rays happen in this point according to symmetrical directions in relation to the normal one, supplying radial sensitivity and in the plan of the part. The interferometer is insensitive to the tangential and out of plan displacements.

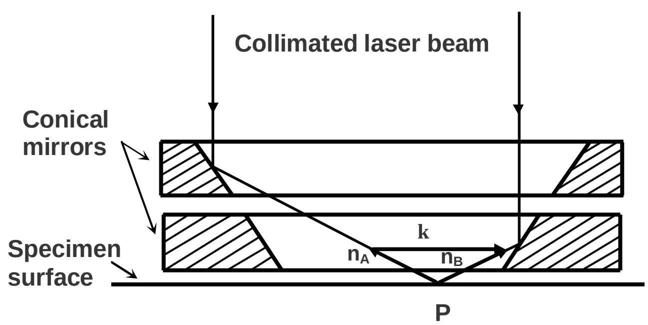


Figure 2.1 Double illumination through the radial interferometer.

The main element of the interferometer is a conical mirror, which is placed near the specimen surface. Figure 2.1 shows a cross-section of the conical mirror containing the mirror axis, which displays two particularly chosen light rays from a collimated illumination source. Each light ray is reflected by the conical mirror surface towards a point ***P*** over the specimen surface, reaching this point symmetrically. The illumination directions are indicated by the unitary vectors $\mathbf{n_A}$ and $\mathbf{n_B}$ and they have the same angle with respect to the axis of the conical mirror. The sensitivity direction is given by the vector ***k*** obtained from the subtraction of the two unitary vectors. Therefore, in-plane sensitivity is reached in point ***P***.

A practical configuration of the radial in-plane interferometer is shown in figure 2.2. The laser light is expanded and collimated by two convergent lenses. The collimated beam is reflected towards the conical mirror using a 45º tilted mirror. The central hole located at this mirror has two main functions: (a) to avoid that the laser light reaches directly the sample surface and to prevent triple illumination, and (b) to provide a viewing window for the CCD camera. The conical mirror is designed to have the split configuration. It is formed by two parts with a small gap between them. The distance of this gap is adopted in such a way that the light rays reflected to the center are blocked. Thus, a small circular shadow is created in the center of the illuminated area and fringe blurring is avoided. A piezoelectric actuator (PZT) was used to join the upper part of the conical mirror. The PZT moves the upper part along its axial direction and allows the introduction of a phase shift to calculate the optical phase distribution by means of the 4-step algorithm or Carré algorithm [3],[5].

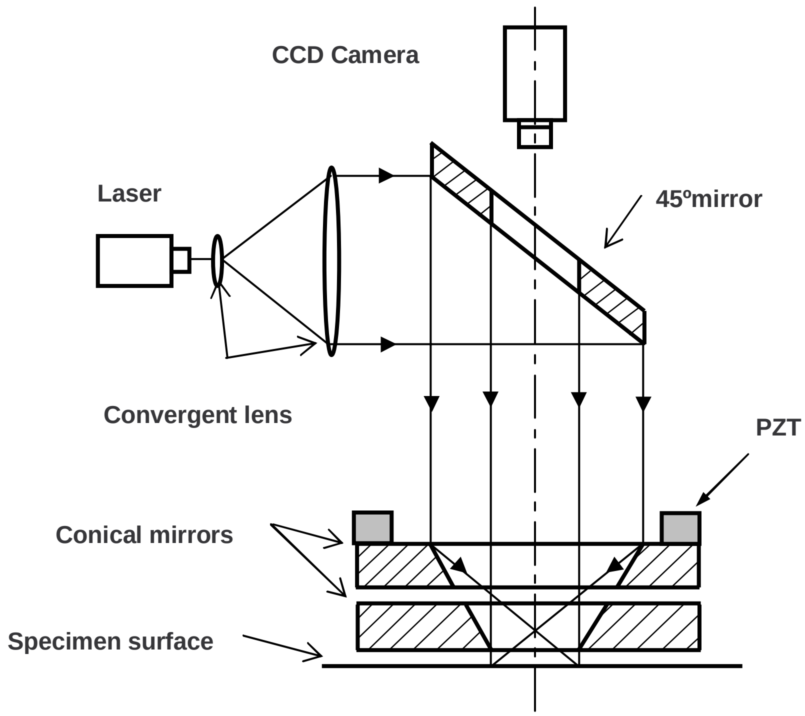


Figure 2.2 Radial interferometer

3 INDENTATION METHOD

Basically the indentation method consists of applying load at the indentation device on the specimen surface. The localized stress on the surface is almost three times bigger than the yield stress [12]. The residual stresses state can be qualitatively identified by ESPI. The indentation is carried out using a conical or spherical tip, similar to the used in hardness test [10]. The displacement field around the tip mark reaches a new equilibrium condition after the indentation. The new arrangement can be correlated to the existing residual stress. Figure 3.1 shows an indentation process.

Rodacoski-1997[12] describes that the local plastic deformation is a function of the geometric characteristics, material properties, and the magnitude and direction of the residual stresses initially in the material. Residual stresses using the indentation method can be evaluated as:

- hardness variation measurement.
- relation between force and indentation depth.
- the geometric shape from the indentation.
- deformation or displacement around the indentation.

Hardness variation measurement is not appropriated for material that presents stress variation on surface.

Relation between force and indentation depth use the continua measurement of load versus deep penetration. This method has been studied in the latest years by Giannakopoulos & Suresh [6],[7],[8], and presents some applications to:

- mechanical properties evaluation of material (Young modulus, fracture resistance).
- residual stress amplitude by comparison to another material free of residual stress.
- gradients in elastic properties and yield point evaluation.

Many of these applications have some limitations, because a clear interpretation of results is affected by the material plastic properties [6].

The geometric shape of an indentation consists in knowing the relation between the indentation load and the true contact area. The material properties are very important, but are difficulty to evaluate the contact area and the penetration depth of the indenter.

Measuring the strain or displacement around the indentation area combined with the radial interferometer is apparently the best method to evaluate residual stress. Otherwise, there is not an easy and simple mathematic model yet. This is the subject for futures work. This technique can be useful to identify the signal and the direction of residual stress immediately after the indentation.

Actually it is possible to measure the radial displacement field around surface indentation region using an ESPI radial interferometer [1],[2],[12]. The fringe maps characteristics, repeatability for different loads condition, different kind of materials, and different indenters, are being investigated. The initial experiments in this paper are very useful to identify an adequate mathematical model and to specify the indentation parameters. More work has to be done using finite elements method or genetics algorithms.

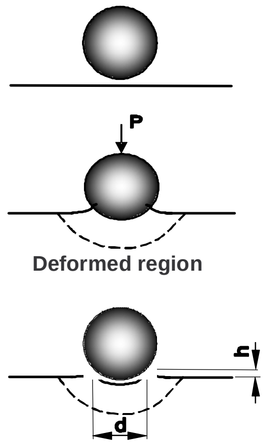


Figure 3.1 Método da indentation

4 EXPERIMENTAL SETUP

The ESPI radial interferometer to residual stress measurement (MTRES) is showed in figure 4.1. The basic system is composed with a diode laser source with wave length 658 nm, a conical mirror with angle of 60° and a CCD camera. The illuminated region has about 10 mm of diameter.

Figure 4.1 ESPI residual stress measurement (MTRES).

4.1 INDENTATION SYSTEM

The indentation system consists of an indenter tip and a support for load application. It was preliminary developed to make testing with MTRES (see figure 4.2). A spherical indenter tip of tungsten carbide with 2.5 mm of diameter and a conical indenter tip of diamond are available to tests.

The indentation system was planned to provide two indentation forms: (1) Known displacements of indentation applied on the material surface with 0.01 mm resolution using a dial indicator. (2) Known loads up to 1875 N of load on the indenter, applying load on the arm of the support system.

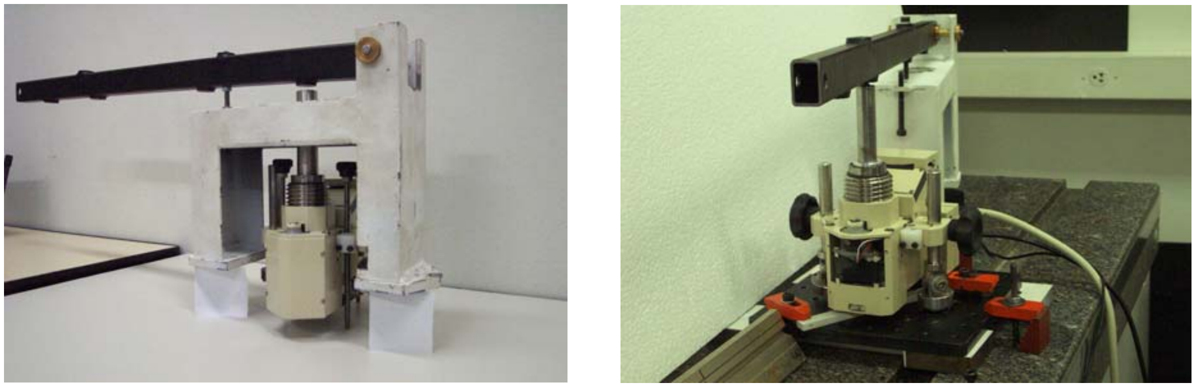


Figure 4.2 Preliminary indentation system and the radial interferometer.

4.2 SPECIMEN

A rectangular aluminum bar with approximately 5 mm thickness was used as specimen (CDP - figure 4.3). The half moon shape in the right part had been produced artificially causing a region with strong residual stresses. The measurement proceeding was carried out in two stages: (1) Displacements field measurement on the free residual stress region. (2) Displacements field measurement near the deformed region, where certainly some residual stress exists.

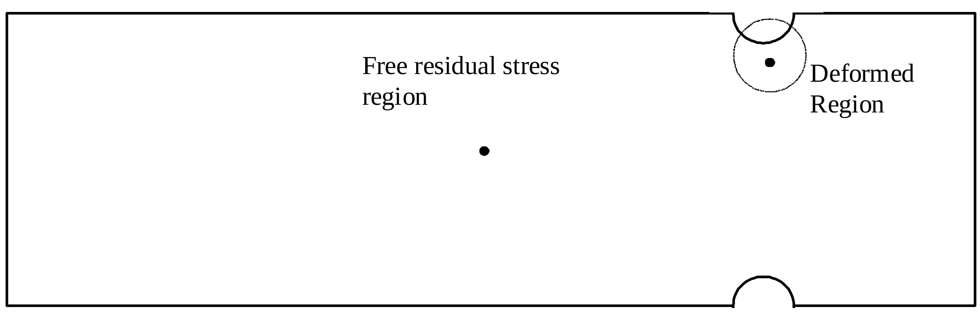


Figure 4.3 Specimen used and indentation region.

5 RESULTS

Figure 5.1 has shown the spherical tip indenter mark with 0.20 mm deep. Figure 5.2 shows the phase shifting map after indentation in the free residual stress region and in the deformed region.

By comparing figure 5.2(a) and figure 5.2(b), it can be observed that the combined system simply allows identifying regions with and without residual stresses. It is also very important to note that due to the radial symmetry of the in-plane interferometer it is not a difficult task to determine the principal direction of the residual stresses from the wrapped phase maps - figure 5.2(b).

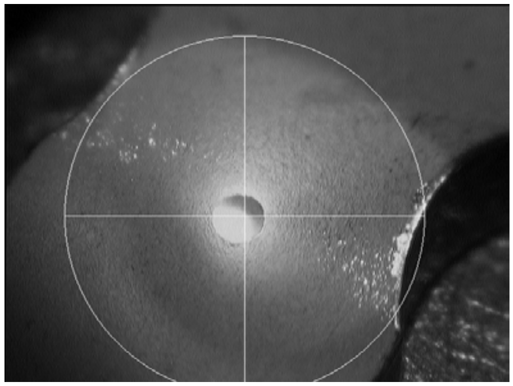


Figure 5.1 Indentation mark. Depth: 0.20 mm

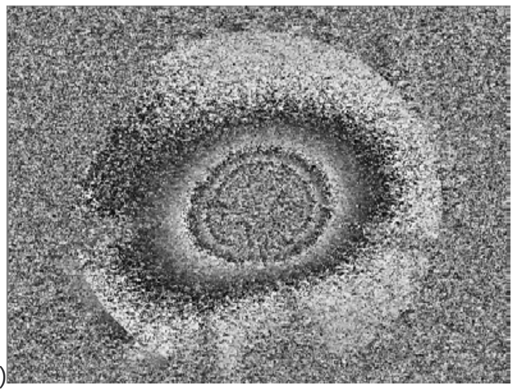
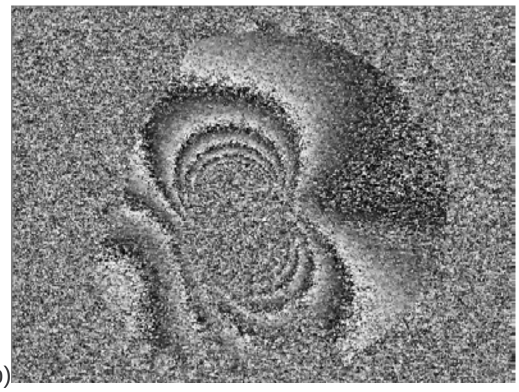
(a)  (b) 

Figure 5.2 Displacement phase map round indentation.
(a) Free residual stress region. (b) Region with residual stress (near deformed region).

6 CONCLUSIONS

This paper present an example that shows a strong potential application for the radial interferometer associated with the indentation technique. New systems can be developed for residual stress measurement. This kind of measurement system enables *in "situ"* measurement of residual stresses and promise to be faster than the hole-drilling technique using strain gages or ESPI. The indentation technique is a very interesting method to release residual stresses because it is non-contact, almost non-destructive and also cleaner than the drilling process since no metal chips are produced.

The combined system allows a simple identification of regions with residual stresses when compared to stress free surface. If an adequate mathematic model is used for evaluation, this technique can replace or attend other measurement ranges.

Due to the radial symmetry of the in-plane interferometer, the principal directions for the residual stress field can be easily determined from the wrapped phase maps. Therefore, it is not necessary to use an ESPI system with a special design for measuring released displacements along two orthogonal directions.

Additional research is necessary for quantitative evaluation involving a numerical solution for this problem with a finite element model to identify a good model turning this technique useful for industrial applications. These investigations will be the object of a future work.

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