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Laser-beam reflection for steel stress-strain characterization

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ABSTRACT

Optical methods had been used widely to measure stress–strain by different contact and non-contact methods. This paper introduces an alternative non-contact method to measure the stress–strain evolution based in one laser-beam reflected in the cross-section of a ductile material while it is under a compression load. We use Gaussian beam propagation equations to calculate the area of the reflected beam and we analyse this area increment applying Digital Image Processing. From this calculation we got a stress–strain diagram and we compare it with the real diagram.

1. Introduction

Stress-strain diagrams are very important to understand the behaviour of materials under different loads [1]; these diagrams are divided into three sections of interest: elastic, plastic and rupture. There are two methods to obtain those diagrams: contact and non-contact. In the former case, mechanics excels doing physical tests such as compression tests in which a material is placed in the universal machine, a continuous load is applied to it and the resulting deformation is measured [2]. Optical methods are also used as an invasive way to determine residual stress, in-field displacements and strain, in which hole-drilling is the most used technique, developed in 1930 by Mathar [3]. Nowadays this technique is standardized by ASTM [4] and has many applications such as measuring the residual stress profile in veneering ceramics [5]; also it is applied for stress quantification [6]. Non-destructive optical methods such as chromatic confocal imaging to estimate surface displacements [7]; multiple laser displacement sensors applied in piping systems [8]; crystal curvature technique during film growths [9]; another one extends conventional Moiré interferometry method to the micron-level spatial domain called micro-moiré interferometer [10]. Some other techniques as deflectometry [11–13], in which is used light passing through a fringe array for measuring curvatures of objects which are taken as mirrors, the reflected light is observed into a CCD camera and the fringe pattern is analysed with standard phase shift techniques, most of the analysed objects have aspherical shape. Another one uses parallel light beams to measure surface curvatures [14], in which is used a collimated light beam passed through means for producing parallel light beams which are reflected off the surface to fall upon a detector that measures the separation of the reflected beams. Both of them measure deformations that already exist in the samples. Currently there exist some techniques to measure the focal length using coherent gradient sensing [15] and also to measure the radius of curvature [16].

The development of non-destructive testing methods is the main challenge for the assessment of structural elements in existing constructions. This paper presents an alternative method for measuring the stress-strain behaviour of ductile materials, in which we use a laser beam focusing on the cross-section of our sample which is under a compression test. We propose that the material (1018 steel) will act as an optical spherical mirror, as the material is first completely flat and its cross-section will change due to a reaction of the compression test; the laser strikes its surface and this “mirror” will reflect and scatter the beam, therefore the scattered area will increase as the deformation increases. The scattered area is analysed with Gaussian beam propagation equations and it is used Digital Image Processing (DIP) in order to measure each area increasing. This is how we obtain a relation between the beam propagation and the strain, which we propose to be similar to the radius transformation of the steel. We calculate the accuracy, error and sensitivity of the method, as well as a theoretical demonstration of our phenomenological process; assessing that the present work would be a cheap technique as it only uses one laser beam for stress-strain measurements.

In Section 2 we put forward concepts that are used in the present work. Section 2.1 shows the optical part, including the Gaussian beam equation, beam propagation equations and how the focal length is calculated using initial parameters from our laser. Section 2.2 shows the mechanical part, including the well-known stress-strain relation with the Young’s modulus and how we related it to our calculated parameter. In Section 2.3 we present two theoretical demonstrations starting from Gaussian equation and Fresnel diffraction Experimental set-up is

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presented in Section 3, which includes the dimensions of our samples, how compression tests are done and how DIP is taking place. Finally the results and discussion are shown in Section 4, in which there are two plots of interest: the stress-strain diagram which is obtained from the universal machine and the DIP plot which is calculated using a program written in Matlab®.

2. Theory

2.1. Gaussian beam analysis

The simplest beam and the most known is the Gaussian, because its characteristics and evolution are well-known [17]. The amplitude function represented from Gaussian beams could be deduced by applying boundary conditions in the optical resonator where the laser radiation is produced, this amplitude is described by

$$E(x,z) = E_0\frac{w_0}{[W(z)]^2}\cdot exp\left[\frac{-x^2}{[W(z)]^2}-\frac{kx^2}{2R(z)}-kz+\eta(z)\right], \quad (1)$$

where w_0 is the beam waist, W (z) is how the beam propagates, R (z) is the curvature radius of the spherical waves and η (z) is the beam phase angle [18]. Gaussian beams are able to pass through different media; the light reflexion occurs when it arrives to the boundary separating two media of different optical densities and some of the energy is reflected back into the first medium [19], taking this outset, if a laser-beam strikes a mirror, the reflection can be studied as a Gaussian propagation. In our case, the metallic surface will be modelled as a convex mirror. As it is well-known, there is a relation between the focal length and the curvature radius of a mirror. Using this relation the phase of the transmitted wave is altered to

$$\varphi(x,z) = 2\eta(z)-\frac{kx^2}{z\left(1+\frac{z_0^2}{z^2}\right)}+\frac{kx^2}{f}, \quad (2)$$

where z_0 is the initial Rayleigh distance, w_0 is the initial beam waist, and f is the focal length of the mirror [20]. There are also propagation equations, in which w_0 and z_0 turns into w_1 and z_1 respectively, after a distance f and they are calculated by:

$$w_1 = \frac{w_0}{\sqrt{\left(1+\frac{z_0^2}{f^2}\right)}}, \quad (3)$$

$$z_1 = \frac{f}{\left(1+\frac{f^2}{z_0^2}\right)}. \quad (4)$$

This pair of equations involves how Gaussian beam propagates [20], so in order to calculate the new beam waist in the propagation axis we have:

$$W(z_p) = w_1\sqrt{\left(1+\frac{z_p^2}{z_1^2}\right)}, \quad (5)$$

where W (z_p) is the new beam waist at z_p which is the propagation distance. One of the aims of the present investigation is to deduce a relation between the radius transformation of the compressed material and the real strain; all these equations are needed in order to calculate the change of the focal length of the material during the compression test. Substituting Eqs. (3) and (4) in Eq. (5) is deduced:

$$\frac{z_p^2}{z_0^4}\cdot x^2 + x\left(1-\frac{W(z_p)^2}{w_0^2}\right)-z_0^2 = 0. \quad (6)$$

W (z_p) is calculated doing DIP, taking 54 area increments per second during the compression test. Once is obtained the result from Eq. (6), the variation of the focal length is determined applying

$$\xi = \frac{f_f-f_i}{f_i}, \quad (7)$$

where f_f is the final focal length and f_i is the initial focal length, thus a dimensionless variable is obtained.

2.2. Compression tests

Physical tests are used in order to know mechanical properties of materials and compression test is one of these tests which enable the user to understand the behaviour of a material under a continuous axial load; from this test we obtain the stress-strain diagram [2]. In this work we are working with samples of 1018 steel of 2.5 × 2.5 × 2.2 cm. and they undergo compression test according to ASTM E-9 [21]. The tests were performed with a speed ratio of 0.2 cm/s up to 90 MPa approx. Since we are working on the elastic part of the diagram, therefore we can apply Hooke's law:

$$\sigma = E\cdot\varepsilon, \quad (8)$$

where σ is the stress, E is the Young's module of the material (200 GPa) and ε is the dimensionless strain. We propose a similar equation to the Hooke's law to obtain a relation between the focal length and the stress:

$$\sigma = E\cdot K\cdot\xi, \quad (9)$$

where K is a dimensionless coefficient proposed in this work and ξ is the dimensionless value obtained in Eq. (7). The coefficient K is obtained from the relation between the slopes of both graphs of interest: stress-strain diagram and DIP plot.

2.3. Theoretical demonstration

The laser used in the present work has initial parameters such as (initial intensity, beam waist and Rayleigh distance) enlisted by the manufacturer in its handbook [22].

In Fig. 1 we plot Eqs. (1) and (2) substituting the results from Eq. (7), the initial parameters of our laser and propagating formally a Gaussian beam. Using analytical expressions for numerical calculations, we show that the focal length increase is proportional to an increment of the beam waist. We assume that $\varepsilon \sim f$.

According to the Fresnel diffraction and a focal lens transmission [23] we have:

$$U_f(u,v) = \frac{\exp\left[\frac{ik}{2f}(u^2+v^2)\right]}{i\lambda f}\iint_{-\infty}^{\infty} U(x,y)\cdot t_A\cdot\exp\left[\frac{ik}{2f}(xu+yv)\right]\mathrm{dxdy}, \quad (10)$$

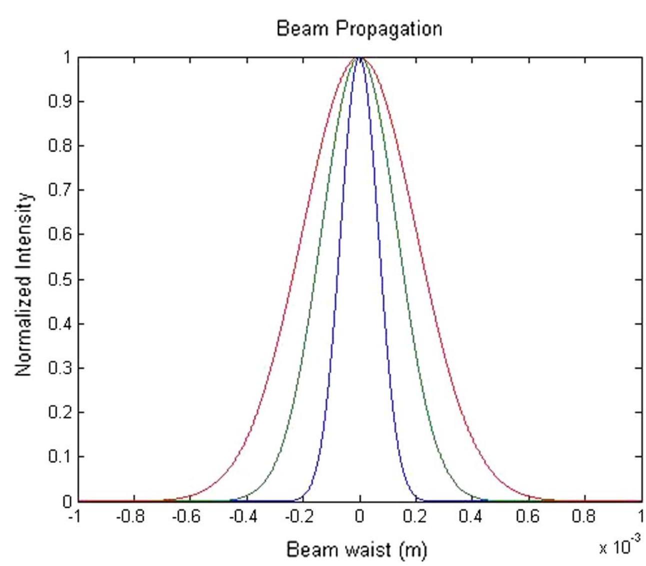

Fig. 1. Gaussian propagation: Intensity profile.