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Uncertainty analysis for non-uniform residual stresses determined by the hole drilling strain gauge method

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ABSTRACT

Due to its simplicity and low cost, the hole drilling strain gauge method is one of the most popular techniques to determine residual stresses. The Standard ASTM E837-13 distinguish between constant and variable stresses in depth. Each type of measurement has an associated uncertainty. The goal should be the quantification and reduction in its magnitude to be acceptable for the purposes of the measurement. Uncertainty estimation associated with this method has not been addressed in depth. The present work deals with uncertainty calculation in the determination of non-uniform residual stresses by the integral method. A general estimation procedure by Monte Carlo method, where many uncertainty sources have been considered, is presented. In normal experiment condition, most of these sources are significant and the irrelevant ones have been identified. Monte Carlo method verifies that a measurement uncertainty evaluation with the GUM uncertainty framework can be performed.

1. Introduction

The strain gauge hole drilling method proposed by Mathar in 1934 [1] describes the drilling of a small shallow hole in the surface of the specimen. An adjacent strain gauge is able to register deformations in the specimen during the process. Deformations arise when stresses contained in the specimen are released with the material removal.

By measuring deformations, original stresses can be calculated. In case of non-uniform stresses, the integral method can be used [2]. Integral method calculates the influence of the relieved stress in the given depth which, however, changes with the total depth of the hole. Although there are some other methods to decode non-uniform stresses [2–4], integral method is conceptually and algebraically simple and is the method followed in this article.

The hole drilling strain gauge method is standardized in ASTM E837-13 [5]. It uses a particular case of the integral method. Although the experimental procedure is not widely addressed in the ASTM E837-13, there are some references that deal with it extensively [6,7].

The method is physically limited by the Saint-Venant Principle, which indicates that the surface strain response quickly becomes insensitive to the effect of interior stresses existing at increasing distances from the measurement surface. Due to this physical limit, a painstaking experimental procedure is essential for the quality of the measurement. After experimental technique, there are two mathematic strategies that can be used to improve the effects of the experimental defects. The first strategy is to evaluate the measured strains in a small number of hole depth increments, with steps larger as the hole depth increase [8]. This is the technique used in this work. The other technique is to use the Tikhonov regularization [9] and it is the technique considered in ASTM E837-13.

There are some references dealing with the uncertainty of the hole-drilling strain gauge method.

Oettel summarize and classify the uncertainty sources in Ref. [10]. Scafidi et al. present a procedure to evaluate the stress uncertainty in the case of uniform stresses [11]. They propose procedures for the correction of the main deviations in order to overcome if one or more of the experimental influence parameters fall out of the corresponding standard limitations. These deviations are the thermal effects, the hole-rosette eccentricity, the hole-bottom fillet radius and the plasticity effects. Unfortunately, the correction of these errors is not always possible regarding non-uniform stresses. In the case of thermal effect, the correction is

Abbreviations: MCM, Monte Carlo Method; GUF, GUM uncertainty framework.

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possible. A correction for the eccentricity is available [12–14] but it is not directly applicable to the integral method. To date, it is not possible for the correction of hole-bottom fillet radius and plasticity effect for non-uniform stresses. This work is only applicable (except thermal effects) to the case where the experimental parameters fall in the ASTM E837-13 and therefore the influence of these uncertainty sources are almost negligible.

Vangi examined the effects of measurement uncertainty sources on the evaluation of residual stresses with the integral method [15]. He considered uncertainties associated with the relaxed strains and the hole diameter. Independent strain deviations with constant values for all measurement are also contemplated.

Zuccarello evaluates the stress uncertainty in order to optimize the calculation steps in the evaluation of residual stress with the integral method [8]. Only relaxed strains are taken into account because other experimental sources produce stress uncertainties proportional to the actual stress. If the other experimental sources are taken under consideration, it would not be possible to obtain any useful prior indication for the stress uncertainty. In order to overcome the non-independence of the strains uncertainty components between the different depths (they arise from the same sources), the strain increments instead of the strains are considered since their correlation is far weaker.

Schajer and Altus describe a method for calculating the stress range that has a specified probability of containing the actual residual stresses with the integral method [16]. They consider uncertainty components associated with strains, hole depths, hole diameter and material constants. It is assumed that these uncertainty components have statistical normal distributions with zero mean and they are independent of each other and each one is linearly combined. A calculation strategy is followed to overcome the violation of the assumption of error independence when all error types exist at the same time.

Prime and Hill propose a new approach to estimate combined uncertainty in residual stress inverse solutions and to select the order of the series expansion [17]. They consider the covariance between fit parameters and the article is mainly focused in the incremental slitting method. Two sources are considered: fitting model uncertainty (*model error* in the literature) (ability of the chosen series expansion to fit the actual stress variation) and strain uncertainty.

The present work is focused on the correct uncertainty estimation of non-uniform residual stresses determined by the hole drilling strain gauge method. The probable uncertainty sources have been taking into account since strain uncertainty is not always the only significant uncertainty [16,17]. Monte Carlo method (MCM) is proposed to propagate the uncertainty [18]. MCM implies some advantages over application of GUM uncertainty framework (GUF) [19]: simpler and more manageable expressions, the possibility to evaluate all the uncertainties at same time and a quite easy input of correlated variables. In addition, MCM avoids some of the limitations of the GUF: the use of a linear approximation in some cases can be inadequate and the output probability density function can departs appreciably form a normal distribution. With these considerations, some of the simplifications and approaches used sometimes in the previous works are avoided: few uncertainty sources and independence, linearity, zero mean, constant values and normal distribution of the variables. As an example, the calculation process proposed is applied for the case of Ti6Al4V laser peened metallic sample. The possibility of applying of these particular results to other materials and treatments, the limitations of the GUF and the influence of some sources will be explored. Finally, the example is compared with the uncertainty that would be obtained following the Ref. [16].

2. Relationship between strains and stresses

In preparation for the uncertainty analysis, this part concisely reviews the integral method [2].

Measured relaxed strains in j (number of hole depth steps so far) are denominated ε_1, ε_2 and ε_3. They have been measured with a rosette with three strain gauges oriented to 0°, 45° and 90° respectively. The stresses in the directions of 0° and 90° are denominated σ_1 and σ_3, and the shear stress normal to these directions, τ_{13} (Fig. 1).

If k is the sequence number for hole depth steps (Fig. 2), with $k \leqslant j$, the following relations can be considered:

$$p_j = (\varepsilon_3 + \varepsilon_1)_j/2 \tag{1}$$

$$q_j = (\varepsilon_3 - \varepsilon_1)_j/2 \tag{2}$$

$$t_j = (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)_j/2 \tag{3}$$

$$P_k = ((\sigma_3)_k + (\sigma_1)_k)/2 \tag{4}$$

$$Q_k = ((\sigma_3)_k - (\sigma_1)_k)/2 \tag{5}$$

$$T_k = (\tau_{13})_k \tag{6}$$

The integral method formulation carries the following matrix relations (where the bar accent indicates a matrix and the arrow accent a vector):

$$\bar{a}\vec{P} = \frac{E}{(1+\nu)}\vec{p} \tag{7}$$

$$\bar{b}\vec{Q} = E\vec{q} \tag{8}$$

$$\bar{b}\vec{T} = E\vec{t} \tag{9}$$

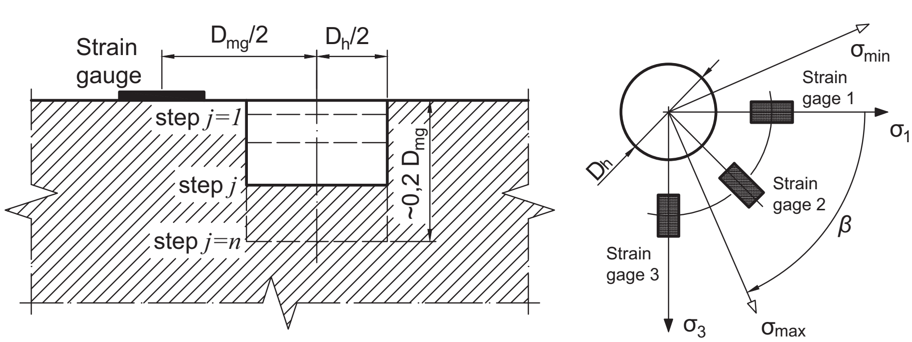

Fig. 1. Gauge placement, drilling location and sequencing.