Measurement of Residual-Stress Distribution by the Incremental Hole-Drilling Method

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ABSTRACT—The hole-drilling method is widely used to measure residual stresses in mechanical components. Recent developments have shown that strains measured on the surface during an incremental drilling can be related to residual-stress distribution. Researchers throughout the world have proposed different calibration methods which lead to more or less accurate results.

The present paper discusses different approaches used. A new calibration method is proposed. We also show how finite-element analysis can be used to determine the correlation coefficients. The variation of the strains measured on the surface for each increment is due to, first, the residual stresses in the layer and, second, the change of the hole geometry. Most authors do not consider the latter aspect. Our results show that this causes a significant error in the experimental data. The finite-element method has been used to compute the coefficients for all types of strain-gage rosettes when the hole diameter is predetermined.

Another problem of the hole-drilling method is the selection of the drilling tool. Two systems have been studied: ultra-high-speed air turbine and conventional milling machine. The method has been applied on both shot-peened and water-quenched test specimens. The results are successfully compared with the bending-deflection and the X-ray method.

List of Symbols

- \( A, B \) = calibration coefficients using the standard elasticity laws
- \( A_{in}, B_{in} \) = calibration coefficients for the geometry \( n \) and the loading \( i \)
- \( d \) = hole diameter
- \( E \) = elastic constant
- \( h \) = mean radial direction of the central grid
- \( \Delta h \) = increase in the depth of the hole
- \( r \) = radius, distance from the center of the rosette to any point on the gage center line

- \( U \) = displacement calculated by the finite-element method, for the geometry \( n \) and the loading \( i \)
- \( \bar{U}_{in} \) = nondimensional displacement
- \( X_1, X_2 \) = principal directions
- \( Z \) = present depth of the hole
- \( \theta \) = angle between the direction \( h \) of the lines of the central grid and \( X \)
- \( a_1, a_2 \) = principal stresses
- \( \epsilon \)' = strain measured in three directions
- \( \epsilon \) = nondimensional displacement
- \( \epsilon_{mn}, \epsilon_{nm}, \epsilon_{mn} \) = total strain measured on the surface after the hole is drilled to the depth \( h \) (in \( \epsilon'_{mn} \) stands for measured)
- \( \epsilon_{mn}, \epsilon_{nm}, \epsilon_{mn} \) = surface strain changes due to the release of stress in the \( n \)th layer only
- \( \nu \) = Poisson's ratio

Introduction

The residual stresses induced by the fabrication process into the surface layers of the processed material superimpose the service stresses and alter their distribution, especially in the first layers of the surface where, in most cases, fatigue or stress-corrosion cracks initiate. The fatigue strength of the material is reduced or increased depending on whether the residual stresses increase or decrease the in-service tensile stresses. It is important, therefore, to take this effect into account when designing the parts. To do this, it is necessary to measure precisely the level and distribution of the residual stresses induced by various fabrication processes.

To solve industrial problems, a great deal of measurement methods have been devised, such as (1) the hole-drilling method, a traditional means of measuring residual stresses with no gradient; (2) the bending-deflection method, measuring the distribution of residual stresses in plane parts; (3) the Sachs method for cylindrical parts; (4) the residual-stress source method for the provision of the residual stresses induced by shot peening; and (5) the X-ray diffraction method for the measurement of surface stresses.

Until recent years, the experimental procedure used and the theoretical expression of the hole-drilling method

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Original manuscript submitted: March 5, 1984. Final manuscript received: October 22, 1984.
restricted its use to the case of the residual stresses distributed uniformly in depth. New developments have brought some improvements. Now a step-by-step drilling procedure allows the determination of the distribution of stresses with depth. Several ways have been suggested for the calculation of the residual stresses from the strains measured after each step of drilling.

The present paper establishes the consensus about the various procedures used, and shows how a calibration by the finite-element method allows the determination of the coefficients correlating the measured strains to the corresponding residual stresses. In order to check the validity of this calibration method, tests on shot-peened specimens and water-quenched specimens have been compared with the bending-deflection method and the X-ray-diffraction method.

'Traditional' Hole-Drilling Method

In the traditional method, the hole is drilled to a depth of up to 1.5 times the diameter of the drill bit. Surface strains are measured by means of the three gages in a rosette, in the center of which a hole is drilled. Thus the mean values of the two principal stresses \( \sigma_1 \) and \( \sigma_2 \) down the hole can be calculated.

To obtain the profile of the residual stresses, the hole is drilled in steps. For each hole depth \( Z \), the surface strains \( \varepsilon(Z) \) are measured. Once the drilling is completed, the residual principal stresses \( \sigma_1(Z) \) and \( \sigma_2(Z) \) can be calculated from equations involving measured values of \( \varepsilon(Z) \) and the calculated correlation coefficients. The essential problem in the measurement of the distribution of residual stresses by the hole-drilling method lies in the determination of these theoretical coefficients. In addition, this new procedure requires the drilling of a flat-bottomed hole which is suitable for each material, will not introduce additional residual stresses in the part at the edges of the strain gages, and will result in a hole geometry as precise and repeatable as possible.

Calibration of the Hole-Drilling Method

There are various calibration methods for the measurement of residual stresses, in particular those suggested by R.G. Bathgate, A. Owens, Measurements Group, Inc., and M. Bijak-Zochowski. The method suggested by R.G. Bathgate and A. Owens is based on the calibration of the coefficients by a uniaxial (or biaxial) loading method, using the finite-element method for the computation. The method consists of loading the test specimen uniaxially (Owens) or biaxially (Bathgate). Since the applied force is known, the applied stress can be deduced. The hole is drilled step by step and for each increment the known stress and the measurement strains are introduced into the equations, hence the coefficients \( A_1 \) and \( B_1 \) for each step can be determined.

In the method suggested by Measurements Group, Inc., the two coefficients \( A \) and \( B \) are first calculated using the standard elasticity laws; then on a tensile test specimen, the relaxation curve for a uniform stress with respect to the hole depth \( Z/d \) is determined. The relaxation of the true stress for each increment \( \Delta \sigma \) during hole drilling is calculated, using the relaxation curve defined previously. For example, when hole depth is changed from \( h_1 \) to \( h_2 \), the percent of stress relaxation \( \varepsilon \) (percent) for the increment \( \Delta h = h_2 - h_1 \) can be found from the curve referred to above. Hence, the equivalent strain, \( \varepsilon(Z) \) is determined:

\[
\varepsilon_i(Z) = \frac{\Delta \varepsilon_i}{\varepsilon_i(\text{percent})} \times 100\text{ percent}
\]

where \( \Delta \varepsilon_i \) is the variation of the surface strain.

By introducing \( \varepsilon_i(Z) \) into the general formulas (see Ref. 17) for the calculation of the residual stresses, the true stress for each depth is obtained. The two methods referred to above are based on the assumption that the values of \( \Delta \varepsilon_i \), as measured for each increment, correspond only to the stress removed, which existed in the layer concerned.

For each layer of material removed, however, there is a redistribution of stresses. In any layer, the same stress produces different surface strains for different hole geometries since, as the drilling of the hole progresses, the geometry of the hole changes. Variations in strain are thus measured at the surface of the part, even if drilling is done in unstressed layers of the material. The strain change measured by strain gages is in this case only due to the change in geometry. M. Bijak-Zochowski and G.S. Schajer have noted the same point. Our calculation method is based on the theoretical work of these authors.

Effect of the Hole Geometry

Calculation of Stresses from Measured Strains

In order to determine the distribution of the stresses in a given material by the hole-drilling method, we made the following assumptions: the material is elastic and isotropic; the measured stresses are below the elastic limit of the material; the component of the stress normal to the surface is negligible; in each removed layer, the stresses are constant (a mean value is used); between successive layers, the shear forces are negligible; the bottom of the hole is flat; the dimensions of the rosette, as defined by the manufacturers, are accurate.

Consider a specimen with an arbitrary distribution of residual stresses. Denote the principal directions by \( \sigma_1 h \) and \( \sigma_2 h \) (it is assumed that these coincide with the axes X and Y) (Fig. 1). A hole of diameter \( D \) and depth \( H \) is drilled. If a stress equivalent to the stresses removed is applied, the state of equilibrium remains unchanged. The equilibrium stresses that existed between the removed layers and the remainder of the part are the radial stress \( \sigma_r \) and the shear stress \( \tau_{\phi} \). (It is assumed that \( \tau_\theta = 0 \).) The reaction of the part to the stresses that are removed by hole drilling is equivalent to its reaction to the application of a stress of opposite sign. In this model, the actual stress distribution is to be replaced by a stepwise-constant distribution (Fig. 2).

In the layer \( i \), the equilibrium stresses \( \sigma_{ri} \) in the direction of \( \theta_i \), before the hole is drilled, can be expressed by two equations:

\[
\sigma_{ri} = \frac{\sigma_i h_i - \sigma_i h_{i-1}}{2} + \frac{\sigma_i h_i - \sigma_i h_{i+1}}{2} \sin 2\theta_i \cos 2\theta_i \tag{1}
\]

\[
\tau_{\phi_i} = -\frac{\sigma_i h_i - \sigma_i h_{i+1}}{2} \sin 2\theta_i \tag{2}
\]

where the angle \( \theta_i \) is the angle between gage No. 1 and the