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The issue of recommended hole diameters in ASTM E837-13a

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Abstract. The paper focuses on assessment of method for non-uniform residual stress calculation published in ASTM E837-13a for case of various hole diameters. The method is an integral method which uses calibration coefficients calculated by finite element method for strain gauge rosette 1/16" and hole diameter of 2 mm. In case of using different hole diameter these calibration constants have to be recalculated using simple formula. The aim of the study was to verify this method of recalculation. Hole-drilling experiment was simulated by using finite element method and residual stresses were evaluated from obtained strains by EVAL-7 software. Simulations were done for 6 different hole diameters. From obtained results it was shown that relative error increases with varying diameter due to recalculation of calibration coefficients. This error can reach values which significantly devalue results of measured residual stresses.

Introduction

Residual stress included in material can be significant factor during loading, because it decreases or increases total stress in a component. One of the most popular and widely used technique for measurement of residual stresses is the hole-drilling method [1]. This method is based on drilling a small hole to a measured component and this causes redistribution of residual stresses around it. After that, relaxed strains are measured by strain gauge rosette and residual stresses are evaluated from these measured strains. Accuracy of evaluated residual stresses depends on many factors, e.g. eccentricity of drilled hole, plasticity effect, process of hole drilling, accuracy of measurement, etc. [1]. One of the significant factors is also a diameter of a drilled hole. The choice of an appropriate diameter of a drilled hole is important because a larger hole diameter leads to bigger strain relaxation, what decreases inaccuracy in calculation of residual stress values, but the use of large diameter can also cause damage of strain gauge rosette [1].

Methods

ASTM E837-13a standard. Residual stresses can be evaluated by EVAL-7 software developed by SINT Technology. This software contains few different methods for evaluating residual stresses, but we focused on ASTM E837-13 Non-Uniform calculation method, especially on its extended version, which contains wide range of usable strain gauge rosettes [2]. ASTM E837-13 Non-Uniform calculation method is integral method which means that in every j-th depth increment relaxed strains are measured by threes gauge grids A, B, C and expressed as

$$p_j = \frac{\varepsilon_A + \varepsilon_C}{2} = \frac{1+\mu}{E}\sum_{k=1}^{j} \bar{a}_{jk} P_k \tag{1}$$

$$q_j = \frac{\varepsilon_A - \varepsilon_C}{2} = \frac{1}{E}\sum_{k=1}^{j} \bar{b}_{jk} Q_k \tag{2}$$

$$t_j = \frac{\varepsilon_A + \varepsilon_C - 2\varepsilon_B}{2} = \frac{1}{E}\sum_{k=1}^{j} \bar{b}_{jk} T_k \tag{3}$$

where p_j, q_j, t_j are measured strain relaxations after the j-th hole depth increment, $\varepsilon_A, \varepsilon_B, \varepsilon_C$ are strain relaxations measured by gauge grids A, B, C, μ is Poisson's ratio, E is elastic modulus, $\bar{a}_{jk}, \bar{b}_{jk}$ are strain relaxations due to a unit stress within increment k of a hole j increments deep, P_k, Q_k, T_k are equivalent uniform stresses within the k-th hole depth increment [3,4]. Residual stresses within the k-th hole depth increment are

$$P_k = \frac{\sigma_{xk} + \sigma_{yk}}{2} \tag{4}$$

$$Q_k = \frac{\sigma_{xk} - \sigma_{yk}}{2} \tag{5}$$

$$T_k = \tau_{xyk} \tag{6}$$

where σ_{xk}, σ_{yk} are normal stresses in x, y directions and τ_{xyk} is shear stress in xy direction within the k-th hole depth increment [3,4]. Value of principal stresses and their orientation can be found by solving system of Eq. 1 - 6, where $\bar{a}_{jk}, \bar{b}_{jk}$ are matrixes of calibration coefficients obtained by simulation of hole-drilling using finite element method [3,4].
ASTM E837-13a standard presents two types of residual stresses: uniform, where stresses are uniform in depth direction and non-uniform, where stresses vary with depth direction [3]. In practice, there is usually not relevant information about type of residual stresses in depth direction and it is more common, due to technological operations, that residual stresses are non-uniform. ASTM E837-13a standard also presents three types of strain gauge rosettes, which are shown in Fig. 1 [3]. The most commonly used strain gauge rosette is type A and its basic dimensions are shown in Table 1, where D is a diameter of a gauge circle, L is length of a gauge grid, W is width of a gauge grid and D_1 is a diameter of a circle on which gauge grids inner edges lie.

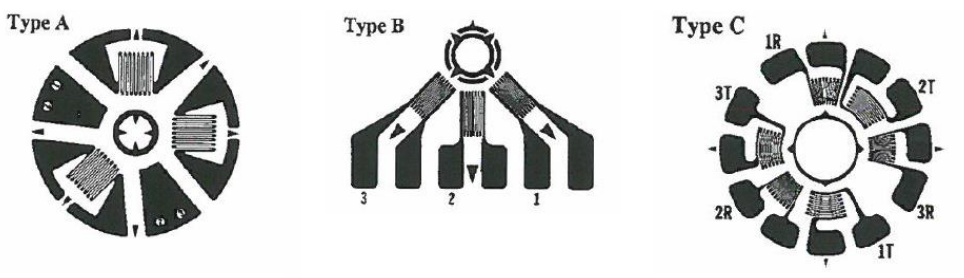

Fig. 1 Strain gauge rosette for hole drilling published in ASTM E837-13a standard [3]

Table 1 Basic dimensions of strain gauge rosettes type A [3]

	D [mm]	L [mm]	W [mm]	D_1 [mm]	D_1/D [mm/mm]
1/32‘‘	2.57	0.79	0.79	1.77	0.691
1/16‘‘	5.13	1.57	1.57	3.56	0.694
1/8‘‘	10.26	3.18	3.18	7.08	0.690

ASTM E837-13a standard publishes only recommended minimal and maximal hole diameters, which differ for uniform and non-uniform residual stresses [3]. It is not clear if these recommended limits are also related to another methods evaluating non-uniform residual stresses and how these limits were obtained. Values of minimal ($D_{0,min}$) and maximal ($D_{0,max}$) hole diameters for strain gauge rosette type A are shown in Table 2.

Table 2 Minimal and maximal hole diameters for strain gauge rosette type A for uniform and non-uniform residual stresses [3]

	uniform		non-uniform	
	$D_{0,min}$ [mm]	$D_{0,max}$ [mm]	$D_{0,min}$ [mm]	$D_{0,max}$ [mm]
1/32‘‘	0.61	1.01	0.93	1.00
1/16‘‘	1.52	2.54	1.88	2.12
1/8‘‘	3.35	5.59	3.75	4.25

We can generalize values of recommended hole diameters also for another similar strain gauge rosette type with linear regression as
-uniform residual stresses

$$\mathrm{D}_{0,\mathrm{min}} = 0.356 \cdot \mathrm{D} - 0.307 \tag{7}$$

$$\mathrm{D}_{0,\mathrm{max}} = 0.595 \cdot \mathrm{D} - 0.518 \tag{8}$$

-non-uniform residual stresses

$$\mathrm{D}_{0,\mathrm{min}} = 0.366 \cdot \mathrm{D} - 0.007 \tag{9}$$

$$\mathrm{D}_{0,\mathrm{max}} = 0.422 \cdot \mathrm{D} - 0.067 \tag{10}$$

Matrixes of calibration coefficients published in ASTM E837-13a standard were calculated by finite element method only for 1/16’’ size type A strain gauge rosette and hole diameter of 2 mm [3]. Published calibration coefficients depend on hole depth and stress depth, which have to be multiplied by 0.5 for case of 1/32’’ rosette and by 2 for case of 1/8’’ rosette [3]. In case of another hole diamter, ASTM E837-13a standard provides a recalculation formula

$$\left(\bar{a}_{jk}\right)_{D_0} = \left(\bar{a}_{jk}\right)_P \left(\frac{D_0}{2}\right)^2 \tag{11}$$

$$\left(\bar{b}_{jk}\right)_{D_0} = \left(\bar{b}_{jk}\right)_P \left(\frac{D_0}{2}\right)^2 \tag{12}$$

where $\left(\bar{a}_{jk}\right)_{D_0}$ and $\left(\bar{b}_{jk}\right)_{D_0}$ are calculated calibration coefficient, $\left(\bar{a}_{jk}\right)_P$ and $\left(\bar{b}_{jk}\right)_P$ are calibration coefficients for a drilled hole of 2 mm, and D_0 is a diameter of a drilled hole [3].

Simulation. Hole-drilling experiment was simulated using the finite element method. By this process, we could avoid adding additional errors due to uncertainty of material properties, technology-related factors (the shape and blunt of the tool, additional stresses created by drilling, etc.) and process of measurement. Parametric model, which allowed easy change of important parameters (geometry, material properties, boundary conditions), was created in ANSYS software. The model is based on the "hole after residual stress" procedure which prescribes residual stress to the solid and relaxed strains are measured after removal of material from the hole. The hole-drilling process was simulated by progressive removal of individual layers of elements. The total number of removed layers and therefore increments of depth was 20.
The model used in calculation consists of thick solid body with uniform uniaxial tension in depth direction. Due to the symmetry of the model, the simulated model consists only of one quarter of the whole geometry. Fig. 2 depicts the geometry with boundary conditions (left) and the finite element mesh around a drilled hole (right) used in simulations.

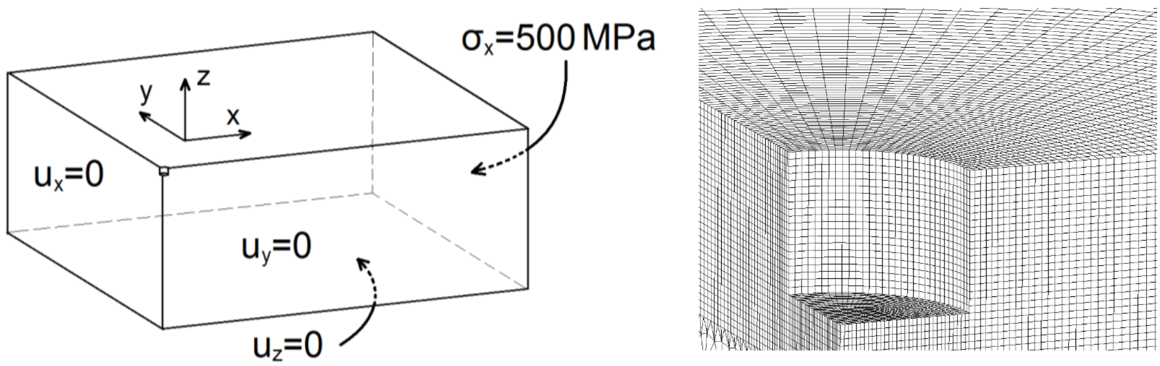

Fig.2 Model of geometry with boundary conditions (left) and the finite element mesh around the drilled hole (right)

For measurement of relaxed strains, a strain gauge rosette 1-RY61-1,5/120S from company HBM was considered. This rosette has diameter of gauge circle D = 5.1 mm, width of gauge grid W = 0.7 mm and length of gauge grid L = 1.5 mm [5]. The relaxed strains were obtained from simulation by averaging nodal strains across the virtual strain gauge grid surface at progressive removal of hole layers. Three strain gauge grids were used; one in principal direction and remaining two rotated by 45 and 90 degrees from principal direction of residual stress. Computational simulations were done for six different hole diameters: 1.6, 1.7, 1.8, 1.9, 2.0 and 2.1 mm. Depth of all holes was 1 mm. Recommended hole diameters for the considered rosette calculated by Eq. 7 - 10 are: $D_{0,min}$ = 1.51 mm, $D_{0,max}$ = 2.52 mm for uniform stresses and $D_{0,min}$ = 1.86 mm, $D_{0,max}$ = 2.09 mm for non-uniform stresses. For study reasons there is a wider range of hole diameters in our simulations than it is recommended for non-uniform residual stress by ASTM E837-13a standard.

Eccentricity of drilled hole and plastic deformations were not considered in simulation since evaluation of results depended mainly on hole diameters. The bilinear model of material with kinematic hardening was used. Properties of the material were the following: elastic modulus E = 210 GPa, tangent modulus E_t = 0 GPa, Poisson's ratio μ = 0.3 and yield stress σ_Y = 2100 MPa. Yield stress was considered so high in order to prevent creation of plastic deformations.
Strains obtained from computational simulations were used as input for EVAL 7 software and ASTM E837-13 Extended Non-Uniform calculation method was used for evaluation of residual stresses. A non-uniform method was used because, in practice, it is common that the residual stress distribution is not known and therefore non-uniform residual stresses in depth direction are assumed. EVAL-7 software contains several calculation methods, so strains obtained from simulations were also evaluated by Integral, HDM and ASTM E837-13 Extended Uniform calculation method [2].
Absolute error of equivalent residual stress was calculated as

$$\Delta = \hat{\sigma}_{\mathrm{eq}} - \sigma_{\mathrm{eq}} \tag{13}$$

where $\hat{\sigma}_{\mathrm{eq}}$ is equivalent evaluated residual stress and σ_{eq} is equivalent simulated residual stress. Equivalent stress was evaluated according to HMH theory. Relative errors were calculated using following equation

$$\delta = \frac{\Delta}{\sigma_{eq}} \cdot 100 = \frac{\hat{\sigma}_{eq} - \sigma_{eq}}{\sigma_{eq}} \cdot 100\ [\%] \tag{14}$$

Results and discussion

Dependences of relative errors on stress depth, evaluated by ASTM E837-13 Extended Non-Uniform calculation method, for different hole diameters are shown in Fig. 3.

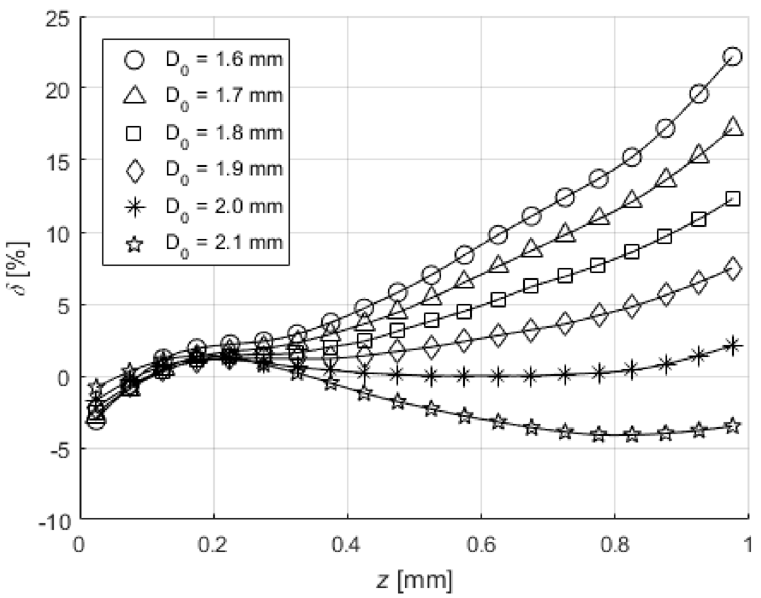

Fig. 3 Relative errors of residual stresses evaluated by ASTM E837-13 Extended Non-Uniform calculation method

Relative errors of evaluated residual stresses in case of drilled hole diameter of 2 mm are small with maximum value 2.1 %. For different hole diameters, relative error increase with increase or decrease in diameter size compared to hole diameter of 2 mm.
These errors, which are a consequence of recalculation process, can reach values which significantly devalue results. ASTM E837-13a standard published range of recommended hole diameters, however from the obtained results, due to high error that occurs for diameters out of this range, these hole diameters should be rather presented as acceptable, not recommended. The choice of range of recommended hole diameters for this method relates to preservation of relative errors in acceptable values.
Relative errors evaluated by ASTM E837-13 Extended Uniform calculation method were very small and for hole diameters of 1.6 - 2.1 mm varied from -0.04 to 0.53 %. Recommended hole diameters for this method are given by requirements for sufficient relaxed strains and for exclusion of strain gauge rosette damage.
Residual stresses were also evaluated by Integral and HDM method. Dependence of relative errors on stress depth evaluated by these methods for different hole diameters are shown in Fig. 4 and Fig. 5.

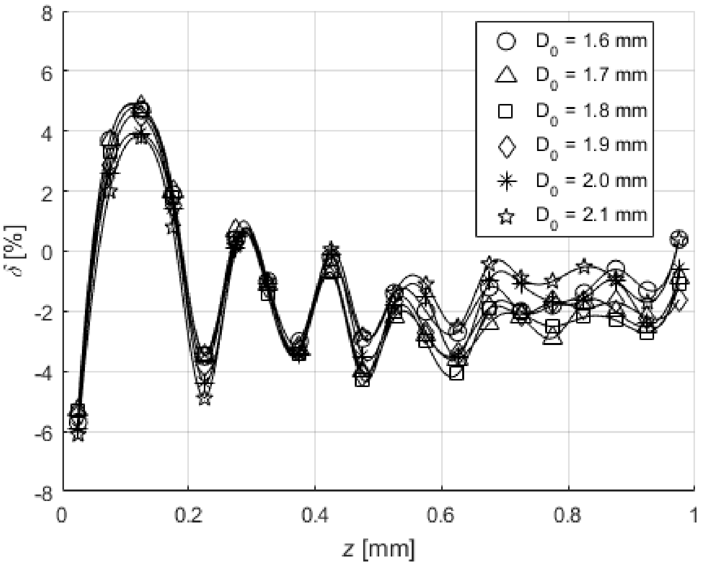

Fig. 4 Relative errors of residual stresses evaluated by Integral method

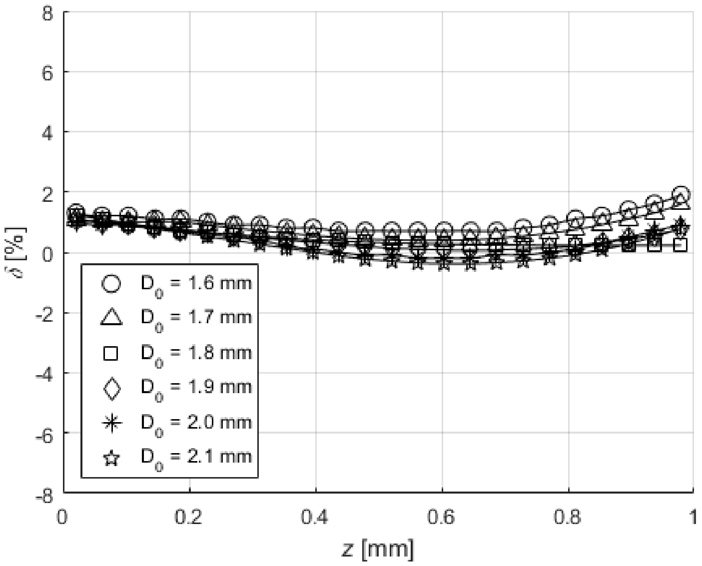

Fig. 5 Relative errors of residual stresses evaluated by HDM method

For both methods, Integral and HDM, errors don’t significantly vary with the change of hole diameter and total errors are small. The range of usable hole diameters for use of these two non-uniform calculation methods is wider than it is published for non-uniform residual stresses by ASTM E837-13a standard.
Because of small errors that occur when evaluating by Integral, HDM and ASTM E837-13 Extended Uniform calculation method, we assume that recommended hole diameters don’t relate to type of residual stresses in depth direction but to a method which is used for evaluation.

Conclusion

Recalculation of calibration coefficients, from their original values for a hole diameter of 2 mm, using formula described in ASTM E837-13a, introduce additional errors into results. These errors can reach values which significantly devalue results of measured residual stresses. It has been also found that the range of recommended hole diameters for non-uniform residual stresses published in ASTM E837-13a is not generally valid for all non-uniform methods, but only for ASTM E837-13a non-uniform calculation method because of recalculation process. Another non-uniform methods (Integral, HDM), included in EVAL 7, have wider range of usable hole diameters than it is published in ASTM E837-13a for non-uniform residual stresses.

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