Advanced Materials Research
ISSN: 1662-8985, Vol. 996, pp 283-288
doi:10.4028/www.scientific.net/AMR.996.283

Online: 2014-08-11

Incremental hole-drilling method vs. thin components: a simple correction approach

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Keywords: Incremental hole-drilling method, correction function, component's thickness, neural network

Abstract. The incremental hole-drilling method is a widely used technique to determine residual stress depth profiles in technical components. Its application is limited in respect to the components geometry, for instance the component's thickness. In this paper, a direct correction of the measured strain relaxations is proposed to consider the impact of deviant geometries, here the component thickness, on the residual stress evaluation that moreover, allows the application of commercially available evaluation software. The herein proposed approach is based on finite element simulation of the incremental hole drilling. The simulated strain relaxations for thin metal sheets are evaluated with an algorithm as used in commercially available evaluation software (i) for uncorrected data as well as (ii) for strain data corrected by the proposed correction procedure. It is shown that the correction approach leads to a significant improvement of the measurement accuracy. Further, by means of the approach residual stress depth profiles in thin metal sheets can be as usual determined using commercial evaluation software for the incremental hole-drilling method regardless of the algorithm used, i.e. differential or integral.

Introduction

In residual stress analysis the incremental hole-drilling method is a widely used technique not least due to the comparative simple instrumentation and its alleged ease of use. Basically, the incremental hole-drilling method is limited in its application concerning the components geometry as for instance thickness, curvature and distance to edges. But, application of the method is often requested, e.g. for structural parts of automotive applications like deep drawn sheet metals (A,B,C – pillars) that are afflicted by residual stresses from their processing route. For local residual stress analysis using diffraction methods the cantilevered components must be sectioned and one has to account for redistributions of residual stresses or in terms of the hole-drilling method the limitations of the method with respect to the components geometry has to be taken into account. Referring to the components thickness different application limits are formulated in the literature (see Table 1).

Table 1: Different application limits concerning the component's thickness.

	ASTM [1]	Kockelmann, König [2]	Sobolevski [3]
min. thickness t	$1.2 \cdot D$	$3 \cdot D_0$	$1.66 \cdot D_0$

Here, D is the rosette mean diameter and D_0 is the diameter of the drilled hole. The application limits of [1] and [2] are rather similar and more conservative compared to the limits given in [3], since residual stress analysis is still reliable although other application limits are reached. In contrast, the limit given in [3] is considering a variation of the component's thickness only. Outside the application limits a reliable evaluation is given by a geometry-specific calibration, which was shown by [3] for application of the differential method. Actually, a geometry-specific calibration is time consuming and leads to a high simulation or experimental effort, since the calibration data is only valid for one set of parameters (i.e. the component's thickness and the hole/strain gauge rosette geometry). Calibration constants have to be calculated separately for the differential [4] and integral method [5,6] if both should be tested. However, commercially available evaluation software as for instance MPA II [4] (differential approach) or H-drill [5,6] (integral approach) does not offer an interface to implement self-calculated calibration data. Hence, the applicant is urged to provide a custum written evaluation program. In this study a new strategy for the consideration of geometry during the stress evaluation that is independent of the chosen hole drilling evaluation method is presented. It is based on a direct correction of the measured strain relaxations that considers the impact of deviant geometries on the residual stress evaluation with the objective to exploit or extend the application limits of the hole-drilling method. The proposed approach provides the application of commercial evaluation software for the residual stress calculation. In this paper, we focus on the constraint ´component thickness´.

Finite Element Simulation

Finite Element (FE-) model. To provide a tool for defined parameter variation and for the definition of the deduced correction function a plane FE-model with dimension of 20 x 20 mm^2 was developed using the software package ABAQUS and elements of type C3D8R. Due to the symmetry of the problem only a quarter of the model was simulated. The drilling of the hole was simulated by stepwise removing the elements in the region of the hole (see Figure 1). Linear elastic material behavior was assumed for steel using the Young's modulus of 210 GPa and a Poisson's ratio of 0.3.

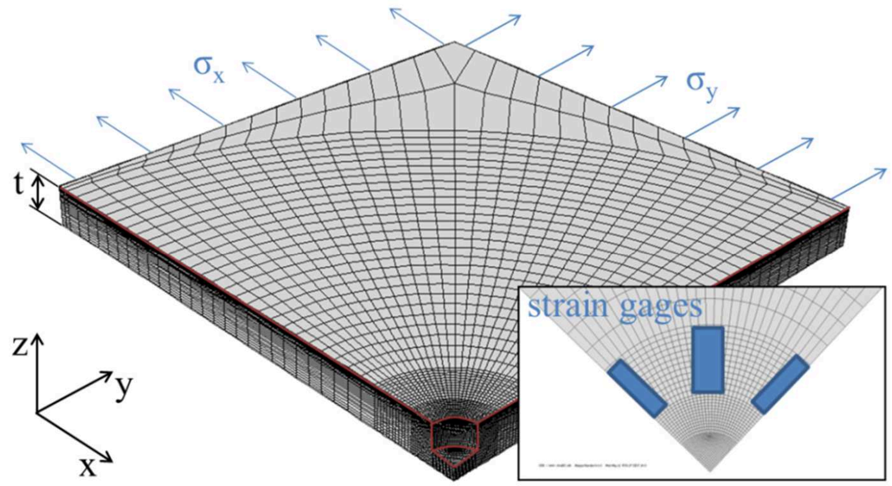

Fig. 1: FE-model for the calculation of the strain relaxations during hole drilling with indication of boundary conditions, applied stress and position of the strain gages.

A nominal stress $\sigma_x = \sigma_y = \sigma_{nominal} = 100$ MPa was applied on the outside surfaces. Using the simulation model a parametric variation was conducted in the way that the thickness t of the model was varied from 1.6 to 6 mm and a hole diameter D_0 of 1.8 mm was defined. Thus, only the effect of the component's thickness on the strain relaxation is considered. Further, the component thickness $t_n = t/D_0$ is normalized by the hole diameter. For each drilling step the released strain was calculated on the surface around the hole. A strain gage rosette design of type B according to the ASTM E837-08 [1] was assumed. Similar to a hole-drilling experiment the strain was integrated and averaged over the resultant gauge area for each strain gage. These strain relaxations were evaluated using the integral and the differential algorithm, respectively. The results were compared to the nominal stress $\sigma_{nominal}$ applied in the simulation and a maximum stress deviation $\Delta\sigma_{max}$ was calculated using the following equation:

$$\Delta\boldsymbol{\sigma}_{max} = \boldsymbol{max}[\boldsymbol{\sigma}_{evaluation}(\boldsymbol{z}) - \boldsymbol{\sigma}_{nominal}(\boldsymbol{z})]. \tag{1}$$

Simulation results and discussion. All results presented here are evaluated using the integral method. The drilling depth z is normalized by the hole diameter D_0 to make the results independent of the hole diameter. Due to the applied axi-symmetric stress state only one stress component is needed to describe the relation between component thickness and stress evaluation. However, it has to be emphasized that the herein proposed approach is not restricted to axi-symmetric stress states. In Fig. 2 the evaluated stress for six different normalized thicknesses t_n are presented.

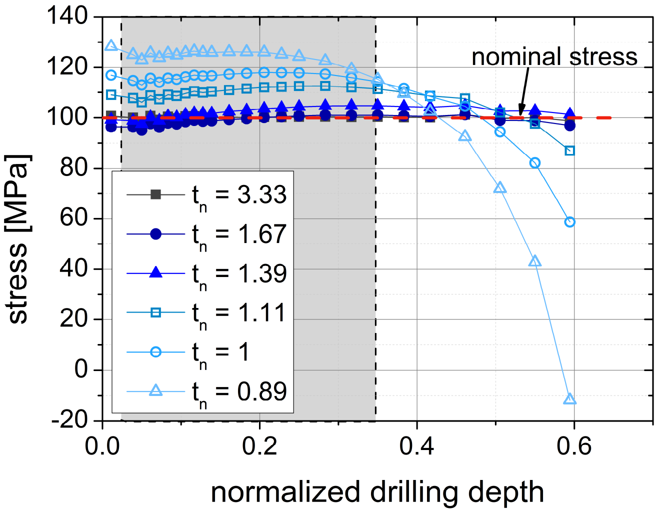

Fig. 2: Evaluated stress depth profiles for different normalized component's thicknesses t_n for a nominal applied stress $\sigma_{nominal}$ = 100 MPa. The simulation was carried out for a hole diameter D_0 = 1.8 mm.

A normalized thickness of $t_n = 3.33$ is almost equivalent to the application limits given in [1] and [2] and the stress depth distribution agrees well with the nominal stress. Hence, a maximum stress deviation of only 2 MPa results. The application limit formulated by [3] is identical to a normalized thickness of $t_n = 1.67$ and a stress evaluation using conventional evaluation software with calibration functions for bulky components leads to a maximum deviation of approx. 5 MPa. Even a normalized thickness of $t_n = 1.39$ results only in a maximum stress deviation of approx. 5 MPa and the stress distribution coincides very well with the nominal stress. With decreasing thickness ($t_n < 1.39$, which corresponds to a sheet thickness of about 2.5 mm for a hole diameter D_0 = 1.8 mm) the evaluated stress increases and the stress distribution is not constant in depth anymore. Within the highlighted area the stress is almost constant but strongly overestimated due to the lower effective local stiffness. For larger drilling depths the stress significantly decreases due to the strong changes in the effective local stiffness and the disruption of the global equilibrium. These general findings correspond with the results shown in [3]. To exclude the very large errors for thin metal sheets that must occur for large drilling depths the data for error analysis according to equation 1 is restricted to normalized drilling depths of 0.35 mm. Furthermore, the surface data are excluded. Using these limits in total a maximum deviation of 13 MPa, 18 MPa and 26 MPa is detected in the highlighted area for a normalized thickness of 1.11, 1 and 0.89, respectively.
Hence, the application limits from literature are confirmed by the simulation results. Geometric boundary conditions, in particular the component thickness has surely to be taken into account during stress evaluation using the incremental hole-drilling method. To correct the deficiency of the method a general procedure is proposed.

Strain correction. In general, the magnitude of the relieved strain increases with decreasing component thickness. This effect is not considered by standard calibration data, which is applied in commercial hole-drilling evaluation software for the calculation of the residual stresses (this is called ´standard´ in the following. I.e. ´standard´ = sufficiently thick). The idea of the new approach for compensating the geometry's influence is a direct correction of the strain relaxations regarding the local stiffness variations due to the geometry. For this reason a correction function $L_{geometry}$ is introduced. This correction function $L_{geometry}$ is calculated through eq. 2 and thus it is a relation between the relaxed strain $\varepsilon_{standard}$ of a (bulky) ´standard´ component within the application limits and the relaxed strain $\varepsilon_{thin\ component}$ of a thin component.

$$L_{geometry}(t_n, z) = \frac{\varepsilon_{standard}(z)}{\varepsilon_{thin\ component}(t_n, z)}. \quad (2)$$

Prior to the stress evaluation the strain relaxations of the thin component $\varepsilon_{thin\ component}$ are multiplied by this correction function to calculate the corrected strain relaxations $\varepsilon^* = \varepsilon_{thin\ component} \cdot L_{geometry}$. Afterwards, the corrected strain relaxations ε^* can be evaluated with commercial evaluation procedures, integral as well as differential method, using their standard calibration coefficients or functions, respectively. Hence, for the critical cases indicated before (see also Table 1), no geometry-specific calibration is required and the correction function is directly applicable independent of the evaluation method used. The complete evaluation strategy is summarized in Figure 3.

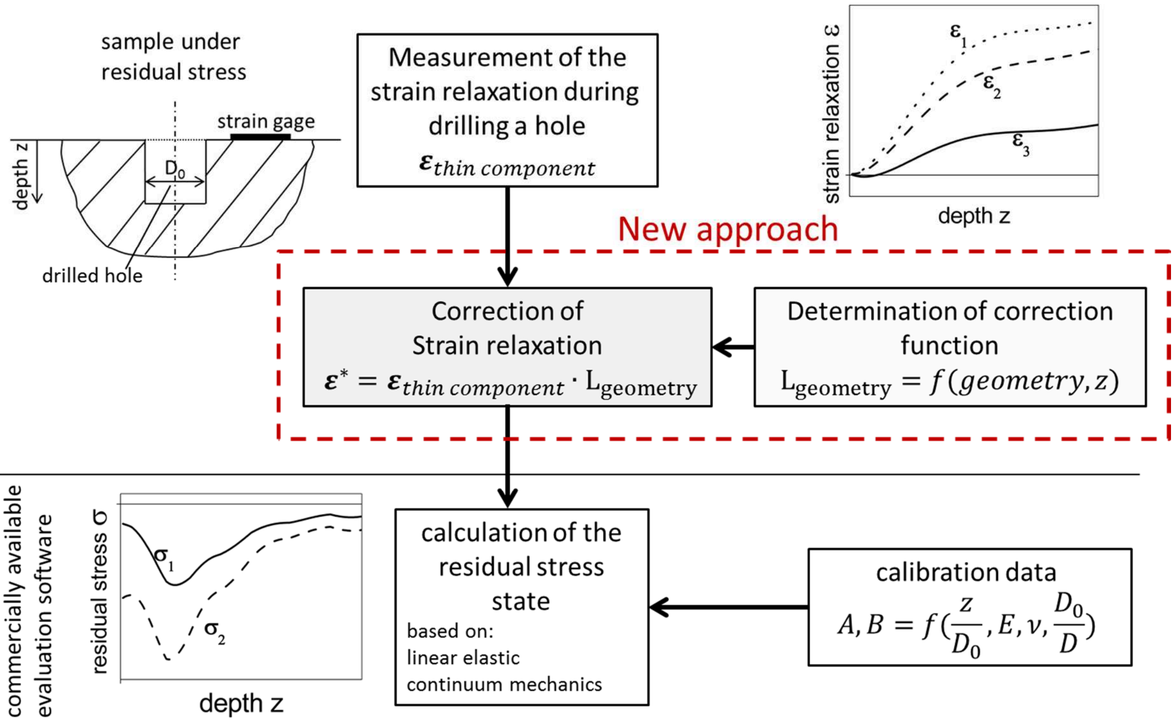

Fig. 3: Evaluation procedure for the hole-drilling method taking into account the influence of the geometry by correcting the measured strain relaxation through an appropriate correction function.

Since the strain relaxations needed for the calculation of the correction function $L_{geometry}$ are determined by FE-simulations the effort appears to be rather high, if various components with differing thicknesses (or with further geometry features that deviate from the ´standard´) are examined. One opportunity to reduce the simulation effort is a linear interpolation of $L_{geometry}$. The error of an interpolation within a normalized thickness increment $\Delta t_n = 0.25$ is less than 1%. Another resort to reduce the simulation effort is the application of artificial neural networks (ANN) for the determination (i.e. the prediction) of correction functions. ANN can be built for example in MATLAB using the neural network toolbox [7]. The necessary training data can be determined by a sufficient number of specific FE-simulations (9 simulations lead to an error of only 0.14%). Hence, the input parameters for the neural network in the present case of thin components are the normalized thickness and drilling depth. After an appropriate training the neural network provides the specific correction function. Thus, it is a useful approach for quickly determining $L_{geometry}$ for any component's thickness within the parameter range. The ANN approach for prediction of correction functions was already established in [8] for the case of layered components and was modified for application to thin components.

In this study the reference thickness was set to $t_n = 3.33$ to determine $\varepsilon_{standard}$. Both strain relaxations $\varepsilon_{standard}$ and $\varepsilon_{thin\ component}$ must be determined using the same hole diameter D_0, rosette geometry, material (E, ν) and stress state. Hence, $L_{geometry}$ is independent of E, ν, D/D_0 and stress state. Thus,

$L_{geometry}$ is not only a function of the normalized thickness but also of the drilling depth (compare to Fig. 4). It can be seen that with decreasing component thickness the correction function is also decreasing due to the increasing strain magnitude. A comparison of the evaluated stress depth profiles with and without the application of the geometry correction is given in Fig. 4. By the correction of the relaxed strain, the maximum stress deviation (in the restricted region) reduces from approx. 26 MPa to about 2 MPa.

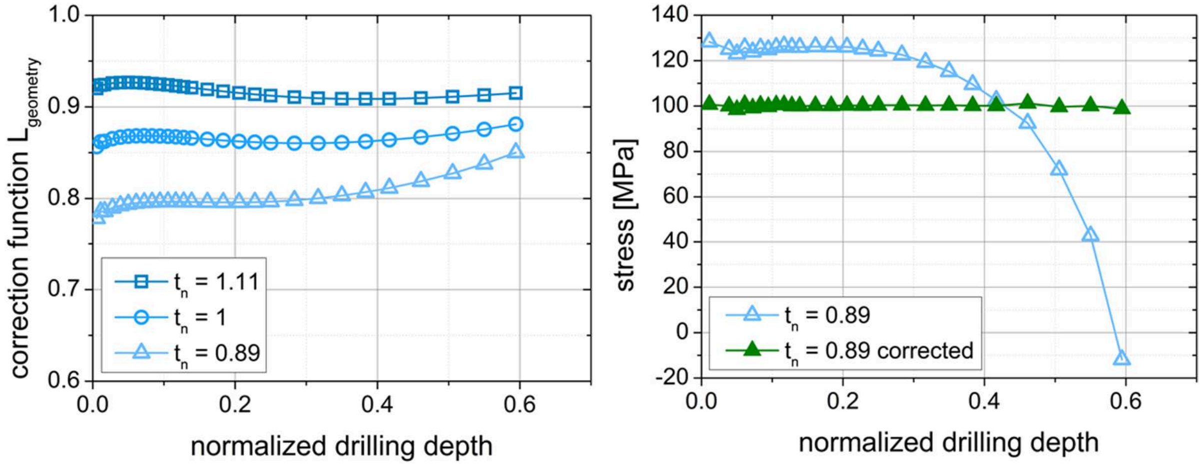

Fig. 4: Correction function for different normalized component thicknesses (left) and the stress distribution with and without thickness correction for a normalized thickness $t_n = 0.89$ (right).

The averaged stress deviation for different normalized component thicknesses evaluated by a standard evaluation can be seen in Fig. 5 and is calculated through eq. 3. Only the constant stress values in the highlighted area in Fig. 2 are considered for the calculation of errors.

$$\overline{\Delta stress} = \sum_{i=1}^{n} w_i \cdot |\Delta stress_i| \cdot 100\% \qquad (3)$$

Where i is the actual drilling increment, n is the number of increments and $w_i = \Delta z / z_{max}$ is a weighting factor, which considers the length Δz of each increment. Hence, the sum of w_i equals one.

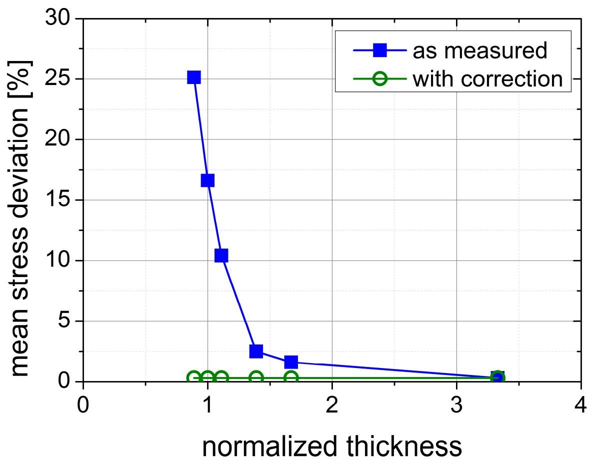

Fig. 5: Mean stress deviation as a function of the normalized thickness for evaluation using the calibration data for bulky components (closed symbols) and for identical evaluation but in combination with the beforehand applied geometry specific strain correction (open symbols).

In the investigated range of component's thickness the mean stress deviation is increasing up to 25% with decreasing thickness. The deviation increases almost exponentially. In contrast, the stress deviation for the corrected stress distribution is on a constant level. Through the presented direct strain correction in combination with a stress evaluation using commercially available software (and the implemented calibration data for bulky samples) a noticeable reduction of the mean stress deviation is achieved which is in tolerable limits with respect to practical application. Thus, using the proposed approach thin components can be examined reliable. Additionally, it should be mentioned that this method can also be applied for the correction of further geometric boundary conditions like for instance the component´s curvature and widths or for application of incremental hole drilling at small distances to component edges.

Conclusion

We demonstrated reliable (residual) stress analysis on thin components for the application of incremental hole-drilling using a new approach for direct correction of the strain relief data. The basis of the approach is the application of correction functions for the measured strain relaxations prior to the stress calculation using commercial available evaluation software. Without application of the correction the herein implemented calibration data/functions lead to erroneous results due to the decrease of the local effective stiffness at the measurement position for which the calibration data in general do not account for. As a consequence the evaluated stress of thin components is overestimated, while thinner components are afflicted with higher stress deviations. With increasing drilling depth a significant decrease of the stress distribution appears caused by the declining change in strain relaxation. The presented correction procedure is a direct method to adjust the relaxed strains and compensate for the geometry's influence. Since the proposed correction is applied prior to the stress evaluation, the approach is well suited for the integral method as well as with the differential method using the identical correction function. In contrast a geometry-specific calibration as proposed in literature [3] has to be determined separately for each evaluation method. We have shown that using the procedure the stress deviation can be drastically reduced, comparable to tolerable deviations that are known for bulky components, i.e. components which are well within the application limit of incremental hole drilling. Further, neural networks were successfully applied for prevision as well as interpolation (i.e. calculation data for various hole diameters).

Acknowledgement. Financial support by the German Research Foundation through project number GI 376/6-1 is gratefully acknowledged.

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