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The Multiple-Incremental Hole Drilling Method: Residual Stress Measurement Uncertainty Quantified

Das Multipel-Inkrementelle Bohrlochverfahren: Messunsicherheiten bei der Eigenspannungsermittlung quantifiziert

Abstract

Up to now the measurement uncertainties of residual stress determinations using the incremental hole-drilling-method had to be assessed by repeating the measurement at equivalent measurement spots or specimens. Often, the requirements for those repetitions are not given or the effort is spared. The determination of the stress state plus the related measurement uncertainty by only one course of measurement is the main feature of the Multiple-Incremental Hole Drilling Method developed by the Fraunhofer Institute for Mechanics of Materials IWM. The method is based on the generation and processing of multiple strain recordings for each depth increment through a stepwise enlargement of the hole in lateral direction. The results show that the new method allows revealing and quantifying measurement uncertainties of the determined stress-depth profile.

Kurzfassung

Bislang waren bei der Eigenspannungsanalyse nach dem Bohrlochverfahren Angaben zur Messunsicherheit nur durch Wiederholungsmessungen an ähnlichen Proben oder Messstellen möglich. Die Voraussetzungen für solche Wiederholungsmessungen sind häufig nicht gegeben oder der Aufwand dafür wird gescheut. Die Ermittlung von Eigenspannungszustand und Messunsicherheit in nur einen einzigen Messablauf wird durch das am Fraunhofer Institut für Werkstoffmechanik (IWM) entwickelte, multiple inkrementelle Bohrlochverfahren ermöglicht. Es beruht of der Erfassung und Auswertung mehrerer Dehnungsauslösungen pro Tiefeninkrement indem das Loch für jede Tiefe lateral inkrementell aufgeweitet wird. Die Ergebnisse zeigen, dass das neue Verfahren in der Lage ist, Unsicherheiten im ermittelten Spannungstiefenverlauf aufzudecken und zu quantifizieren.

1. Introduction

The incremental hole drilling method is an economical and well established method for depth probing of residual stresses within a depth of about 1 mm. Depth probing by competing measuring techniques like X-Ray diffraction is much more elaborate. It is well known that there are several sources of errors which can affect the accuracy of results. As there are only three measuring signals delivered by the common strain-gage-rosettes, which are needed to obtain the lateral stress components and there orientation, no additional information is available to assess the measurement uncertainties. As a consequence, the confidence in hole-drilling measurements often is disregarded as long as no additional information verifies the results. The obvious method to verify the measurement uncertainties, repeating the measurement, is often somewhat doubtful as the availability of an identical specimen or measurement location is questionable. In addition, one of the attractive features of the method, the relatively fast determination of a stress profile, is lost if several repetitive measurements have to be performed. Different attempts may be possible to solve this disadvantage, e.g. the usage of rosettes with more than 3 strain gages [2]. In principle, the methods, based on optical strain field measurement [3, 4] should provide enough information to calculate measurement uncertainties. Nevertheless, up to now one could hardly find results of hole-drilling measurements with the measurement uncertainty quantitatively indicated.

The lack of quantitative information about the measurement uncertainty of a single hole drilling measurement has been a great disadvantage of the method and has been limiting its acceptance for component assessment and quality control severely. In addition, the certification and standardization of the method is hindered.

2. Basic Principles of the Common Incremental Hole Drilling Method

The hole-drilling method is a partly destructive method that follows always the same measuring sequence. First a standardized strain-gage-rosette is applied at the measuring area. Three strain-gages are arranged on each rosette. This is necessary to determine the complete plain residual stress state which is given through the principal stresses and their orientation. Then an exactly defined cavity is machined at the center of the Rosette. Every removal of a material volume causes a rearrangement of the equilibrium of the stress state. This is accompanied by the generation of surface strains which are registered by the strain gages near the cavity. From the strain readings the released residual stresses are calculated using calibration functions describing the relationship between the strain development at the surface and the released stress state. These calibration functions can be derived from measurements on specimens with a well known stress state or by Finite Element calculations. Common strain rosettes provide three strain component readings at azimuthally angles of 0°, 45° and 90° which is sufficient to calculate the plain stress state.

For the incremental hole-drilling method the machining of the cavity is done stepwise down to the predefined depth. Different machining techniques were developed (e.g. air-abrasive, electro-discharge-machining [5, 6]). Nowadays the most common technique is high-speed-drilling. It is important, that the drilling method does not induce significant plastic deformation to the material.

Different calculation methods are available to evaluate the originally existing residual stresses states from the strain readings. They can simply be classified into differential and integral methods. Since the integral methods afford relatively complex numerical models for a variable geometry of the hole, a differential method was used for the investigations presented here. The most common differential evaluation methods are proposed by König [7] or Schwarz [8]. In the following the method of Schwarz is sketched as this method was used in the presented investigations. The calibration functions needed to evaluate the stresses from the strains generated during drilling of the hole are derived from a fit of calculated or measured strain readings for a given (constant) stress. This can be achieved by applying a recursion for each strain direction over the depth. The recursion functions can vary for different calculation methods. Often polynomial functions of higher order (e.g. order 6) are used to achieve differentiable strain-depth functions. For example the equation for the strain calculation in 0 ° - direction (x-direction) is (1):

$$\varepsilon_{nxx}(\xi) = \frac{1}{K_x^2(\xi) - \nu^2 K_y^2(\xi)} \cdot \left[K_x(\xi) \cdot \frac{d\varepsilon_x(\xi)}{d\xi} + \nu \cdot K_y(\xi) \cdot \frac{d\varepsilon_y(\xi)}{d\xi} \right] \quad (1)$$

To obtain the residual stress Hook's law is applied (2):

$$\sigma_0(\xi) = \frac{E}{K_x^2(\xi) - \nu^2 K_y^2(\xi)} \cdot \left[K_x(\xi) \cdot \frac{d\varepsilon_0(\xi)}{d\xi} + \nu \cdot K_y(\xi) \cdot \frac{d\varepsilon_{90}(\xi)}{d\xi} \right] \quad (2)$$

The principal stresses can be obtained by application of Mohr's circle of stress (3)

$$\sigma_{1,2}(\xi) = \frac{\sigma_0(\xi) + \sigma_{90}(\xi)}{2} \pm \frac{1}{\sqrt{2}} \cdot \sqrt{\left(\sigma_0(\xi) - \sigma_{45}(\xi)\right)^2 + \left(\sigma_{90}(\xi) - \sigma_{45}(\xi)\right)^2} \quad (3)$$

with:

ε_{nxx} – *strain in load stress direction* (0°)
ξ – *normalized depth*
K_x – *calibration function* $(0^\circ$ – *direction*$)$
K_y – *calibration function* $(90^\circ$ – *direction*$)$
ν – *poisson´s number*
E – *coefficient of elasticity*
$\varepsilon_{0,90}$ – *measured strain in* $0°,45°,90°$ – *direction*
$\sigma_{0,45,90}$ – *calcualted stress in* $0°,45°,90°$ – *direction*
$\sigma_{1,2}$ – *principal stresses*

Besides the differential methods the Integral-method proposed by Schajer [9] is often used. For this method it is necessary to build up an equivalent FE-Model. Recursion in the manner of polynomial recursion analysis is not needed for this method. Different load-conditions based on polynomial functions over the depth-axis need to be simulated. A quarter-model is sufficient, because of the symmetrical hole-geometry. With a sufficient number of strain-depth profiles developing during elimination of volume elements of material stressed by different loading conditions a linear system of equations can be set up. In addition with the measured data-set this system of equations can be solved. The integral method has not been used for the investigations presented her, as the proposed drilling strategy would result in an enormous effort for modeling the large number of incremental drilling steps and loading assumptions.

2.1 Common Uncertainties of the Incremental Hole Drilling Method

Uncertainties result, e.g., from the accuracy of the machining operation, additional residual stresses introduced by the drilling technique and from more general limitations of the method, e.g., the maximum residual stresses which can be released without plastic deformation due to the notch-effect of the hole [10]. Especially the errors due to inaccuracies of the drilling equipment like the centering accuracy can vary with each measurement and could affect the quality of the results in a significant way. Besides of centering issues also the axial and radial stiffness of the milling-equipment lead to uncertainties which affect the strain measurement. Other measurement uncertainties which are not appropriate to the hole drilling technique itself but for example to the temperature dependence of the strain gauge-rosettes or wiring issues also affect the measurement results. All these uncertainties influence the strain-development at the surface when a cavity is machined. The only measuring data available are the three strain values which can be recorded for each depth-step. This database is sufficient for the calculation of the residual stress state comprising two principal stresses and their direction. Additional information which could be used for calculation of measurement uncertainties is not provided by the common drilling strategy.

3 Numerical Model and Experimental Setup

The basic idea to overcome the lack of measurement data needed for the calculation of measurement uncertainties is to generate multiple datasets at one measuring location by a stepwise increase of the hole diameter. For each individual hole diameter the surface strain generated by the stress release is determined. From this set of data a mean value and the corresponding standard deviation is calculated.

First a feasibility study concerning the machining steps was conducted. Using specimens with typical residual stress states (due to e.g. shot peening, grinding) the dimensions of volume increments needed for a significant strain relieve at the surface were tested. An appropriate step width of 0.1 mm was evaluated for both, lateral and depth increments.

Then two different drilling strategies were investigated. First an incremental lateral expansion for every depth increment beginning from the surface was tested. The second tested drilling sequence starts with a fixed small hole diameter drilled stepwise to the default depth. Then a radial expansion is carried out by a stepwise removal of several hollow cylinders with increasing radius. Both drilling sequences are sketched in Fig. 1.

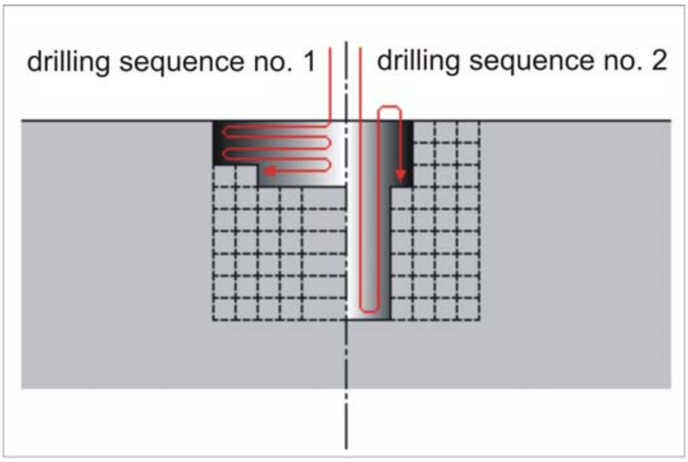

Figure 1: Two possible drilling sequences with multiple stress relieves

Since there was a relatively small strain development evaluated using drilling sequence no. 1, compared to drilling sequence no. 2, drilling sequence no. 2 was used for all further investigations.

For all tests a strain gage rosette due to ASTM E837-01 standard was used. The maximum diameter of the hole (2 mm) was limited by the dimensions of this rosette. The minimum diameter of the hole (1 mm) was limited both by the dimensions of the drilling tool and by the minimum required surface strain generated by the first material removal steps. For each depth increment up to six single datasets corresponding to the lateral enlargement of the hole could be recorded.

Due to the complex shape of the hole drilled by the stepwise enlargement of the hole-diameter the geometry used for the calibration has to be geometrically similar to the geometry of the hole during the real measurement. Thus, for the Multiple-Incremental Hole Drilling Method, the calibration curves are determined best by a numerical simulation of the drilling and strain development process. A FE-Model was created in Abaqus with the grid under the strain gage positions uniformly distributed to satisfy the integrating effect of real strain gages. Figure 2 shows the mesh of the FE-Model which was carried out as a quarter-model due to the symmetry of the problem.

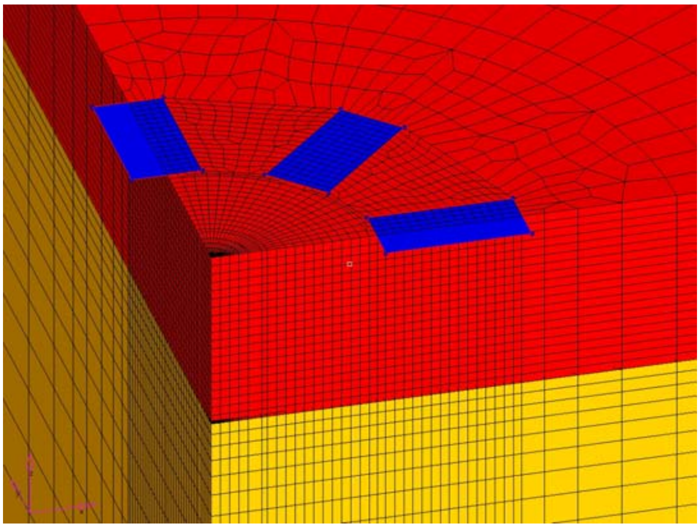

Figure 2: FE-Model for calibration

The model is build up with elastic element properties only. Plastic deformation was not allowed due to the theoretical basis of the hole drilling method although it is well known that local plastic deformation may occur for stress levels well below yield strength. A rule of thumb says [11] that residual stress states with maximum stress values up to 60% of the yield strength can be treated more as less on elastic assumptions.

For experimental testing, a hole-drilling device developed by MTU-Aero Engines was used. Contrary to many other hole-drilling devices, this equipment machines the hole using a drill with a small diameter which enlarges the hole to the complete size by an eccentric circular motion of the drill. Thus, the multiple-incremental hole drilling technique could easily be realized.

To verify the new drilling and evaluation strategy drilling tests on a steel specimen (yield strength 690 MPa) being loaded by a constant tensile stress were performed (see Fig. 3). To avoid effects due to additional unknown residual stresses caused by machining of the specimens two measurements were performed on the same test specimen with an applied stress of 300 MPa and 100 MPa, respectively. After completion of the two measurements the difference of the strain readings for each of the drilling steps were calculated. Thus the contribution of residual stresses was eliminated and the evaluated strain values should correspond to a loading stress of 200 MPa. Consequently, also in the FE Model a loading stress of 200 MPa was applied.

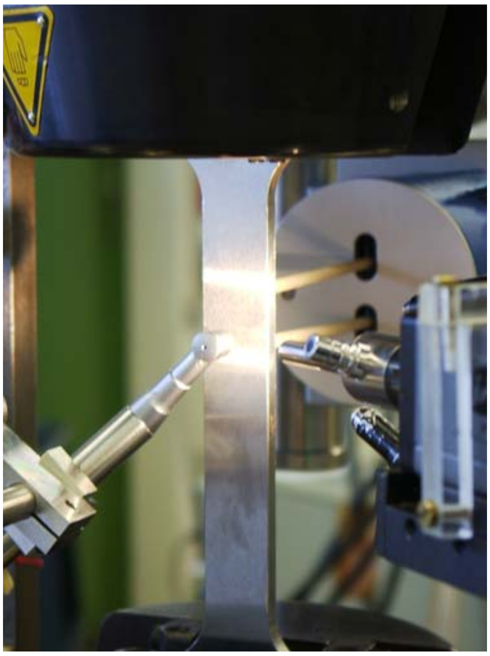

Figure 3: Hole drilling measurements on a test specimen under defined loading conditions

4. Results

4.1 Calculated strain development

Figure 4 shows the development of surface strains in the direction of the loading stress of 200 MPa using the drilling sequence no. 2 (see Fig. 1), calculated by the FE-Model. Before each new enlargement of the hole the initial strain was set to zero to better show the amount of stress relieve due to the elimination of the individual volume elements.

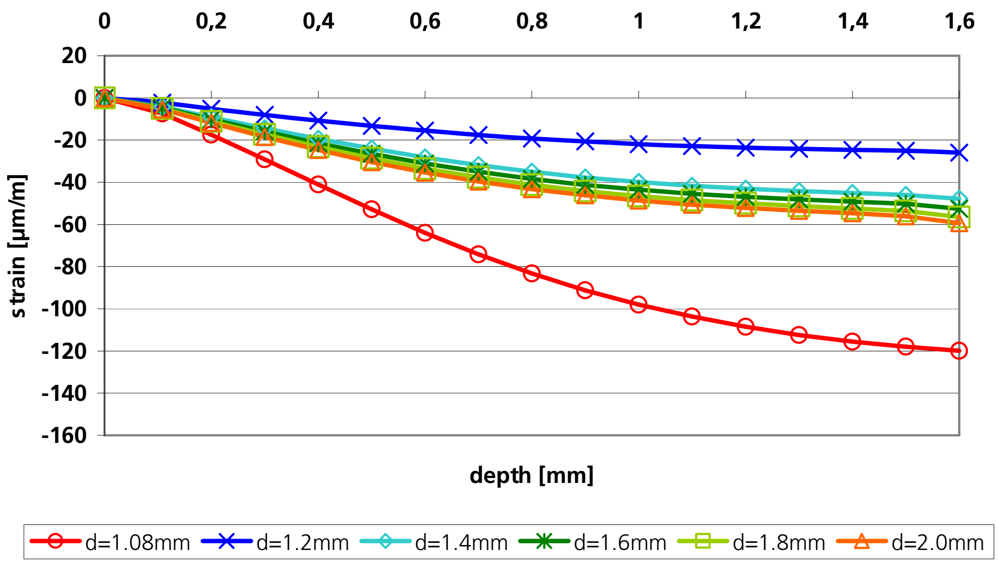

Figure 4: Numerically determined strain development (in loading direction) at the surface for increasing hole-diameters (tensile load stress of 200 MPa)

The results show a high strain generated by the first drilling cycle followed by more or less comparable amounts of strain generated by the enlargements of the hole. Though the strain development near the surface is small, the generated surface strains in total are significant with respect to the measurement sensitivity of the strain gages.

4.2 Measured strain development

Figure 5 shows the development of surface strains in the direction of the loading stress of 200 MPa determined in the experiment. The largest hole diameter was limited to 1.6 mm to avoid delimitation of the strain gage foil. Qualitatively, the measurement and the calculation reveal the same results. Nevertheless, small differences exist for the first drilled hole and in between the subsequently drilled enlargements.

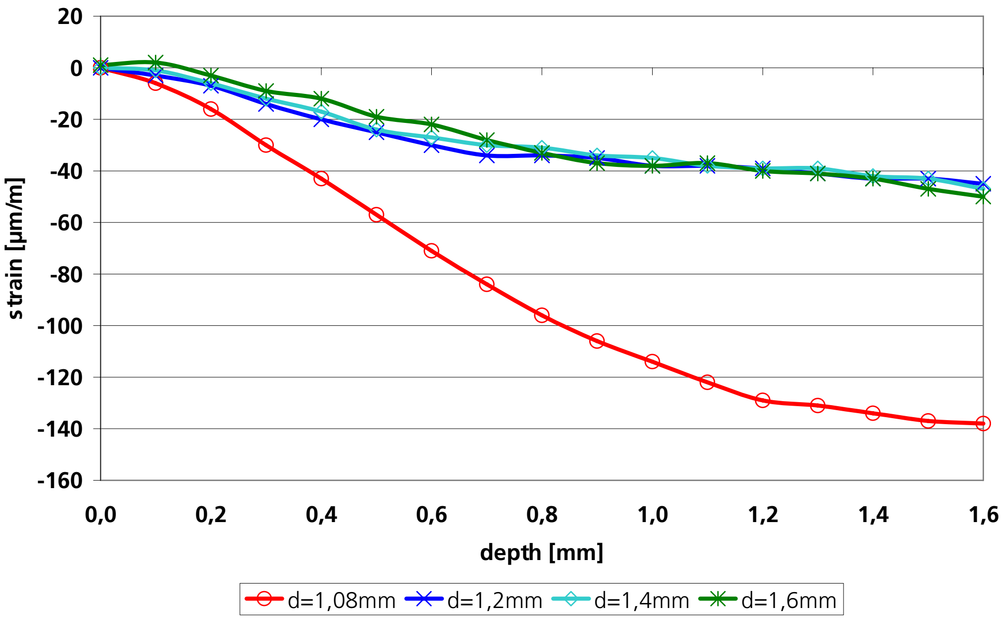

Figure 5: Measured strain development at the surface for increasing hole diameters (four cycles) in direction of the tensile load stress of 200 MPa

4.3 Evaluation of stresses and measurement accuracy

The differential calculation method of Schwarz [8] was used to calculate the stresses for the individual hole diameters. The calibration functions describing the dependency of the generated surface strains on the stress state were taken from the results of the FE-calculations of the strain development during drilling (see Fig. 3). A recursion routine based on a 7^{th} order polynomial function was used to fit both, the FE-data and the measured data. From four single drilling cycles the mean values and the standard deviations of stresses for each drilling depth were calculated. Figure 6 summarizes the results.

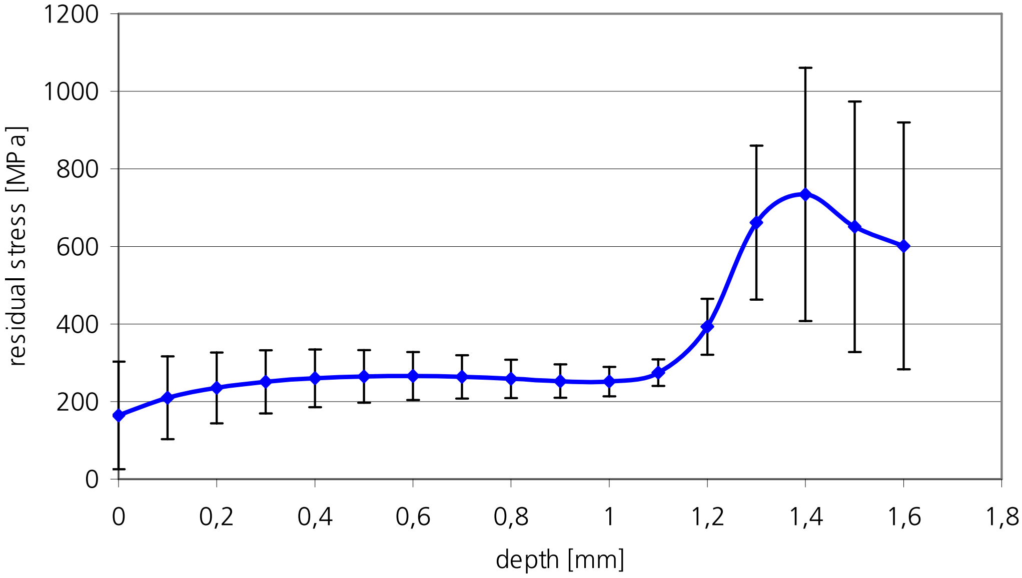

Figure 6: Mean stresses in direction of the tensile load stress (200 MPa) and appropriate standard deviations

The evaluated depth profile now shows a more or less constant stress level within the first 1.1 mm depth. This is in accordance with the homogeneous loading stress applied to the specimen. The amount of evaluated stresses is slightly higher than the applied stress. This may be due to a summation of systematical errors as a consequence of the two measurements performed at different applied loads. In addition, the FE calculations showed some plastic deformation at the bottom of the hole which is not taken into account by the common evaluation methods.

Near the surface a small drop of the stress values is obtained whereas in deeper regions large deviations between the applied and the measured evaluated stress are found.

The determined measurement uncertainties clearly point out the lower measurement accuracies for the near-surface values and especially for the deeper regions. This is in accordance with the common experience of the hole-drilling method being less accurate near the surface and in deeper regions. Thus, the measured stress-depth profile can be assessed on basis of the individual standard deviations of the stress values.

5. Conclusion

The presented investigations show that the new Multiple-Incremental Hole Drilling method comprises detailed and reliable information about the accuracy of residual stress investigations. Contrary to other attempts to determine the accuracy of the measurement results, no additional measurements on comparable measurement spots or specimens are needed. Thus, the assessment of residual stress measurements using the hole-drilling method now can be based on quantitative measures. This should promote the usage of this method also for the assessment of safety and availability of components.

In this paper the new multiple-incremental hole drilling method has been applied to depth probing using the differential evaluation method of Schwarz. Additional investigations [12] confirmed the applicability of the method to other well known differential evaluation methods. It is evident that the additional lateral drilling strategy, on which the Multiple-Incremental Hole Drilling Method is based, can easily be applied to the non-depth resolving standard hole drilling method (ASTM E 837-01].

Further investigations will concentrate on the optimization of the drilling strategy and the numerical calibration model. It is planned to provide commercially available software (patent pending [13]).

Acknowledgment

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