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Residual Stress Measurement Uncertainty of the Hole Drilling Method

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Abstract. The goal of presented work is discussion about residual stress uncertainty evaluation using hole-drilling method based on results of software SINT EVAL 7.2. The uncertainty for some input parameters are presented on model example for homogenous tensile stress field just using integral evaluation method. The results of comparative inter-laboratory test including uncertainties are shown including their evaluation in probability domain. It has been shown that the uncertainty is highest at the surface and at the final drilling depth and for ideal conditions was estimated to be 33 % at the surface.

Introduction

The hole drilling method [1] is standardised for long years [2], [3]. At the same time the test for presence of residual stresses is an objective of many testing laboratories. The estimation of uncertainty must be added to test results also for this type of measurement. The demand for accredited tests goes even further with necessity of comparison of the distributions of obtained results and allowable limits based on probability approach.

During evolution of evaluation methods from the procedure based on one step measurement [4] followed with multiple power series method [5] ending with the integral through profile method [6], [7] the uncertainty estimation became rather bit complicated.

According [3] the uncertainty of determination of the uniform stresses by means of the power-series method is ±10%, no estimation is made for integral method. In [5] an extensive analysis of a measuring error was carried out based on the uncertainties of the most of the input parameters which results in a similar error stated in the standard [4]. The main source of the uncertainties specified herein is the eccentricity of the hole being drilled (5%), stress induced by drilling (5.5%), a diameter of the hole being drilled and the material constants. These considerations are valid if all the requirements of the standard [3] for the measuring accuracy have been met (both the hole misalignment and depth accuracy less than ±0.004·gauge circle *D*, strain reading accuracy and stability ±1 με).

According [1] for incremental hole drilling the maximum uncertainty for given test was about ±40 MPa (15 %) at the surface and ±24 MPa (20 %) on the last drilled layer. The smallest one was estimated in the middle of whole drilled depth.

Calculation of uncertainties of the hole drilling method

Recently introduced software SINT Eval 7.2 [7] includes very good estimation of the uncertainty for several hole-drilling methods used for non-homogenous residual stress profile evaluation. Operator can in detail set the uncertainties and their distributions of all variables, coming into the calculation: Young's modulus E, Poisson's ratio μ, strain measurement ε, gage factor k, hole diameter D_0, zero depth offset z_0, and depth measurements z_i. Some systematic errors can be eliminated e.g. correction of end mill fillet, form of strain gauge rosette, hole eccentricity and elastic-plastic stress state. As a result, the combined stress uncertainty U expanded by a coverage factor k for each evaluated layer is computed, tabled and presented in a chart as upper and bottom tolerance limits around the computed residual stress mean value.

Model example. For examination of the influence of basic input parameters to the resulting uncertainty, the set of 20 released strains was generated at equal steps from 0.05 mm to 1 mm for in depth homogenous tensile stress field $\sigma = 100$ MPa. This was made solving directly the basic equation for integral method and using the relaxation constants given in [3] for 1/16 in. rosette; calculation was made inside MS Excel. The resulting set of released strains ε_{ai}, ε_{bi}, ε_{ci} was loaded to the Eval 7.2 software and the residual stresses were evaluated. The obtained residual stress profile using the ASTM E837-13a method for non-homogenous stress field is presented in Fig. 1, curve $\sigma_{\min}$, $\sigma_{\max}$. The residual principal stresses perfectly fit the input value of 100 MPa which indicates, that both Eval and our calculations were made correctly.

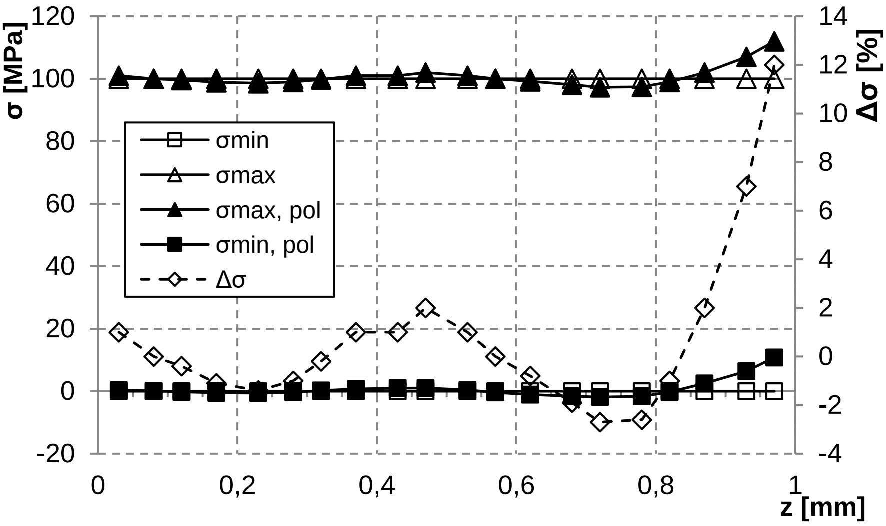

Fig. 1: Ideal stress profile for pure tension and distortion using polynomial interpolation

One of the possible smoothing of measured set of strains before the same calculation (and often used), is to interpolate them with the polynomial. You can see in Fig. 1, curves marked as "pol", what happens, if you use this EVAL option. The evaluated stress field near the whole depth changes to unrealistic value. This result, obtained for ideal calculated strains, may be much worse for real data from the measurement. The reason is that the polynomial may change the slopes of relaxation curves for all gages in another way. The difference in the whole depth causes the lack of the data for the interpolation from the curves right sides. It is therefore recommended to drill the whole some steps (e.g. four) above the required depth.

Using uncertainty computation with the software Eval 7.2 is presented in Fig. 2 again for the above mentioned model example for the pure tension. The tolerance limits for 95.4 % coverage probability were evaluated for two cases of input uncertainties. The first case are pre-set "Eval" values labelled as ±U(σ), the second case are uncertainty values specified by ASTM standard as the worst accuracy of measured strains, hole dimensions and the depth (labelled as ±U(σ), ASTM). In Table 1, these expanded uncertainties are evaluated for three depths including input values for standard deviations of selected parameters. Here also the uncertainty calculation for pre-set input value of measuring amplifier SPIDER8 (third example) and the calculation for the lower accuracy of depth measurement (when the manually controlled device as Vishay RS 200 is used) are presented.

It is obvious, that the highest uncertainties are at the surface and at the whole depth. The uncertainty at the whole depth increases with the increase uncertainty of the measured input values. For pre-set optimistic parameters the uncertainty is about 33 % at the surface and 23.3 % at the whole depth; for lower input uncertainties the stress uncertainty may reach about 100 %. On the other hand, the uncertainty in the middle depth does not change significantly from depth 0.3 mm to 0.7 mm (uncertainty is here lower than 10 %).

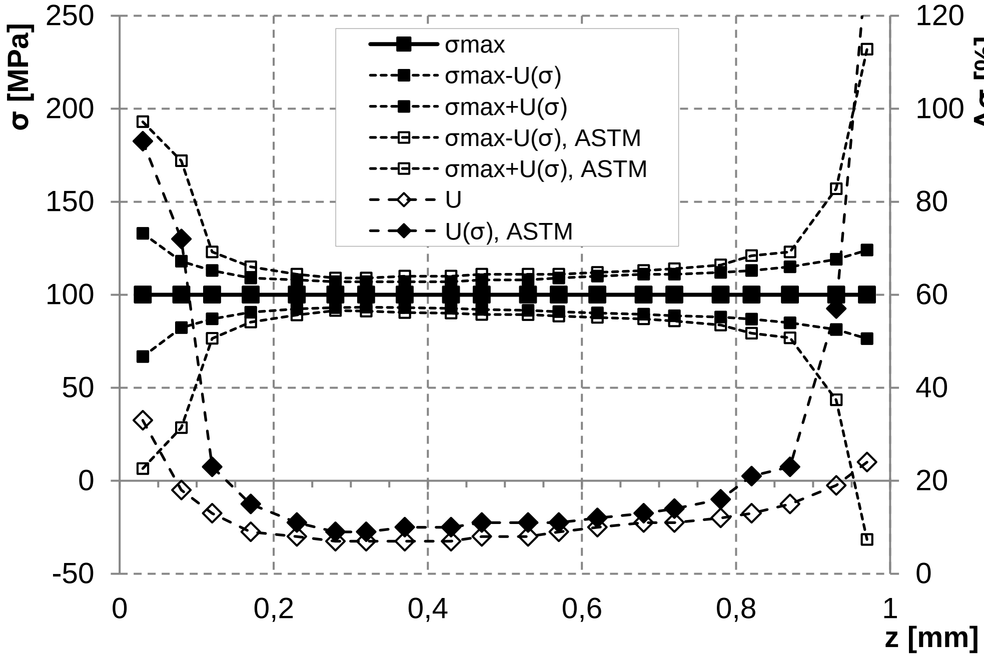

Fig. 2: Uncertainty tolerance limits for pre-set and critical ASTM input uncertainties

Table 1: Uncertainty at three depths for selected input parameters

Uncertainty estimation	Parameters		Pre-set	Depth with lower accuracy	SPIDER8	ASTM
Material	*E*	[%]	3	3	3	3
	μ	[%]	2	2	2	2
Gauge factor	*k*	[%]	1	1	1	1
Amplifier			pre-set	pre-set	SPIDER8	pre-set
	ε	[μm·m^{-1}]	0.32	0.32	1.83	0.32
	class	[%]	0.05	0.05	0.1	0.05
Hole (turbine)	D_0	[mm]	0.01	0.01	0.01	0.02
Depth	zero depth	[mm]	0.01	0.01	0.02	0.01
	accuracy	[mm]	0.001	0.01	0.02	0.001
	step by step	[mm]	0.002	0.01	0.02	0.002
	repeatability	[mm]	0.002	0.01	0.01	0.002
Uncertainties	$U(\sigma)_{z=0.05}$	[%]	33.3	52	75.5	93.4
	$U(\sigma)_{z=0.35}$	[%]	6.8	7.4	7.6	8.6
	$U(\sigma)_{z=0.95}$	[%]	23.6	62.5	86.2	128.6

Using the uncertainties of the hole drilling method in praxis

Comparative tests. The comparison of evaluated profiles of residual stresses measured on a bisected part of the railway axle made from annealed A1N steel (Fig. 3) using the software [6] was performed. Three different drilling techniques were used: high speed air turbine with SINT MTS3000 (D_0=1.8 mm), low speed end mill with Vishay RS200 (D_0=4 mm and 2 mm) and end mill with SINT MTS3000 (D_0=4 mm) (both 30000 rpm). Here only the minimum principle stresses of two drilling techniques made with air turbine (RTI) and end mill (VZÚ) are presented (Fig. 4). The upper and lower tolerance limits (stress uncertainty U(σ) for k = 2) for both laboratories are drawn with dashed lines. The most of the input values of uncertainties were chosen from EVAL 7.2 database and the rest was estimated. The standard [3] requirements for the input uncertainty were not exceeded. For the evaluation the EVAL ASTM E837-13 advanced method was used.

Fig. 3: Investigated half section of the axle and used drilling device Vishay RS-200

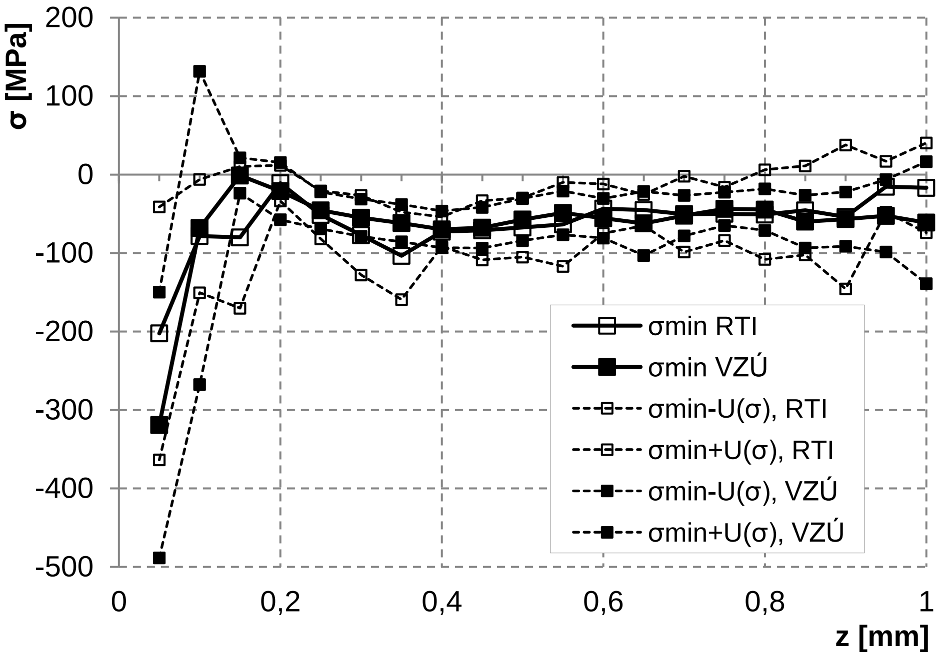

Fig. 4: Compared residual stress profiles including tolerance limits for 2 drilling techniques

The largest differences between evaluated residual stress profiles are at the surface and in the 1 mm depth, which corresponds to the uncertainty tolerance limits.

In Fig. 5 (left) only the upper tolerance limits for the results from the laboratory VZÚ are presented. It is interesting, that depth profile for real measurement is not as smooth as in model example and is a function of the stress values at individual steps. This observation is valid also for relative uncertainties. In real measurement the evaluated stress profile is also not ideally smooth. The large changes between steps may probably be caused also due to drilling errors. Good praxis may be to compare these changes with the uncertainty envelope – the changes should be inside the tolerance limits (Fig. 5, right). In other way it is necessary to correct the uncertainties of input parameters.

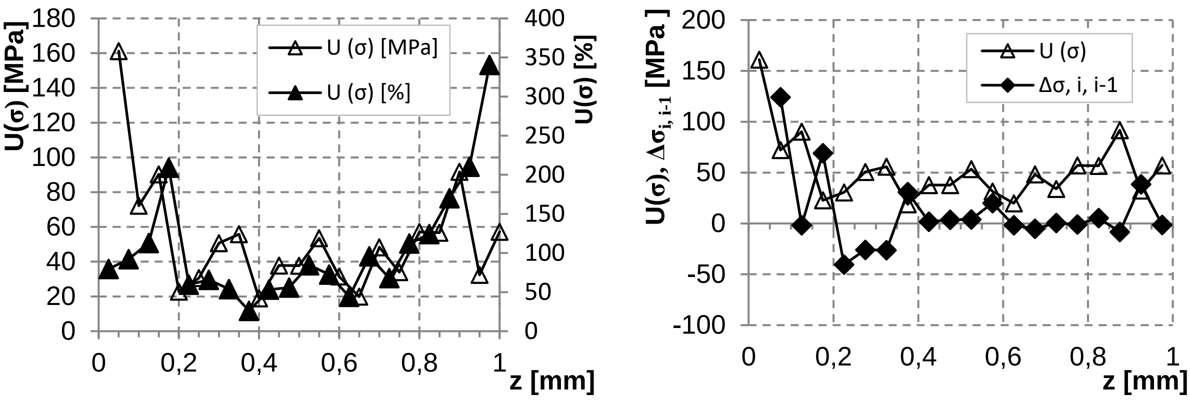

Fig. 5 Error analysis of real measurement (left absolute and relative values, right comparison of the uncertainty with the stress difference between two adjacent steps)

Uncertainty assessment. For obtained uncertainties it is necessary to decide, if the results are good or bad. For here presented inter laboratory test is good praxis to compare the results using the E_n – score (1), calculated from combined expanded uncertainty for each step. For satisfactory results this factor should be within the interval ±1.

$$E_n = \frac{\sigma_1 - \sigma_2}{\sqrt{U_{\sigma_1}^2 - U_{\sigma_2}^2}} \tag{1}$$

Obtained profile of this comparative characteristic for presented inter-laboratory test is presented in Fig. 6, left. From the point of view of this assessment the most problematic are the middle depth, where the theoretical uncertainties are low, which for the higher differences of mean values can cause unsatisfactory results.

For laboratory tests it is necessary to make assessment of coincidence of the results with the customer specification. This was made using mean values in the past. However the probability assessment has to be made at present. E.g. for our presented test the measured residual stress near the surface has to be lower than the limit value of 100 MPa. An example of this access is made in Fig. 6, right. The distribution of uncertainties at the surface, in the middle and the whole depth are presented here with Gaussian approximation. It is obvious, that the evaluated stress on all depth is lower than 100 MPa with probability approaching level 1. Should the mean measured value be more closely to 100 MPa and the probability density function wold intersect the limit value, the fulfilling the specification would be with lower probability, which might not be accepted from the customer. This is the driving force for the increasing of the accuracy measurement of the testing laboratories.

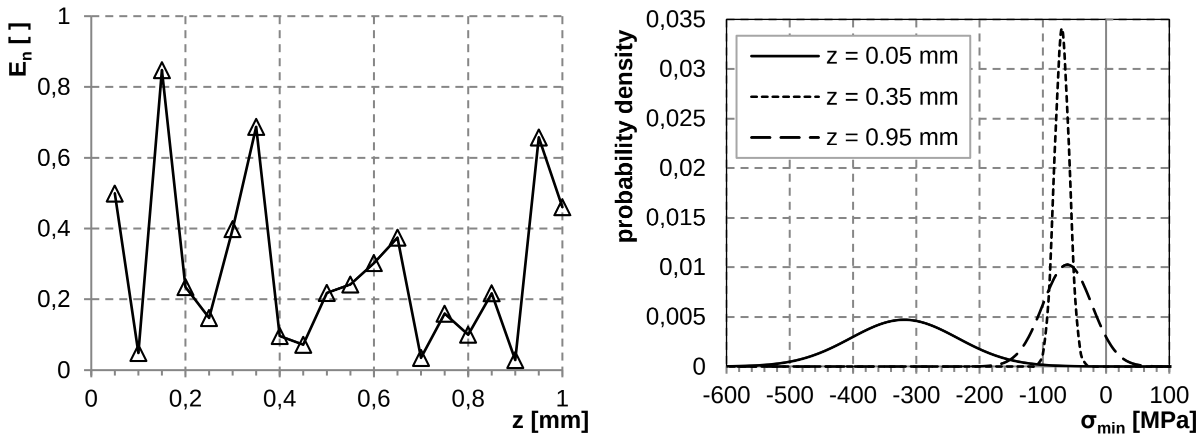

Fig. 6: Uncertainty assessment – inter-laboratory test (left), uncertainty probability (right)

Conclusions

It was shown, that the uncertainty of the hole drilling method is for high accuracy measurement with stepping motor about 33 % at the surface, 8 % in the middle depth and about 24 % in the whole depth. With decreasing the measurement accuracy the uncertainty increases especially at the whole depth. Using ASTM recommended limits of the measurement accuracy the uncertainty increases at the whole depth about one order.

The uncertainties of input values to the calculation of resulting uncertainty have to be selected very carefully, otherwise unrealistic low or high values can be obtained.

The resulting uncertainties have to be included to the measurement results because it is common praxis that the results are given for 95.4 % probability. If the limit stress is e.g. 100 MPa at the surface, the specification is fulfilled, when the measured mean value is max. 67 MPa.

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