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Groove grinding method for near the surface residual stress measurement

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Abstract. The grove grinding method for the semi-destructive measurement of residual stresses near the surface is presented in the article. The principle of the method is that an annular grove is ground perpendicularly to the surface and the stresses are calculated from the relieved strains at the strain gauge positioned near the groove. The calibration coefficients for one-dimensional distribution of residual stresses for homogenous stress profile and for stresses changing with the depth using integral method were derived and a handy tool for grinding the grove was developed. Initial measurements on rectangular bar are presented and compared with hole-drilling method.

Introduction

Residual stress is an important parameter in respect of the failure of a structure or mechanical component. Positive near the surface residual stresses can significantly lower the fatigue strength of the structure. Several technics are available for subsurface residual stress measurement as hole-drilling, ring-core, slitting and X-Ray or ultrasonic methods [1]. Here proposed groove grinding method is a modification of the slitting and hole-drilling methods. It can be applied for one dimensional distribution of residual stresses normal to the surface plane near to the surface.

Theoretical considerations

The principle of the method is that an annular grove is ground perpendicularly to the surface and the stresses are calculated from the relieved strains at the strain gauge glued perpendicularly on given distance from the groove edge with the help of calibration constants. The real dimensions of used grinding disc and strain gauge position are visible in Fig. 1.

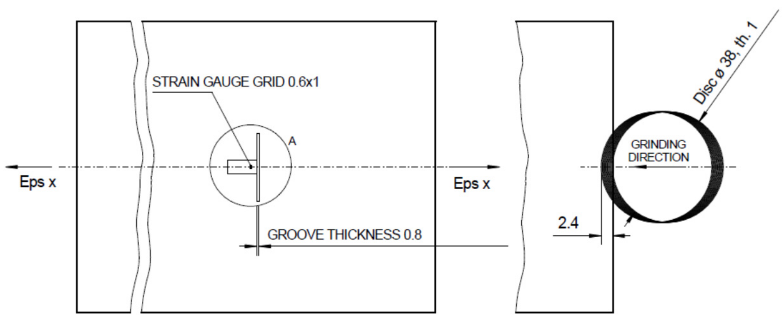


Fig. 1: Principle of the groove grinding method

Theory. A shallow annular grove is incrementally ground to the object surface at the depth z_i and the residual stress σ_{xk} at the depth z_j is estimated using linear elasticity theory from relieved strains ε_j, measured at one or more linear strain gauges, glued near to the edge of the groove.

$$\varepsilon_i = \frac{1}{E}\sum_{k=1}^{j} a_{jk} \cdot \sigma_{xk} \quad (1)$$

The calibration constants a_{jk} indicate the relieved strain in a groove j steps deep, due to unit stresses within groove step k.

Using the integral method, the residual stresses within each groove depth step can be computed from measured strains solving the matrix equation

$$\bar{\boldsymbol{a}}\boldsymbol{\sigma} = E\boldsymbol{\varepsilon} \quad (2)$$

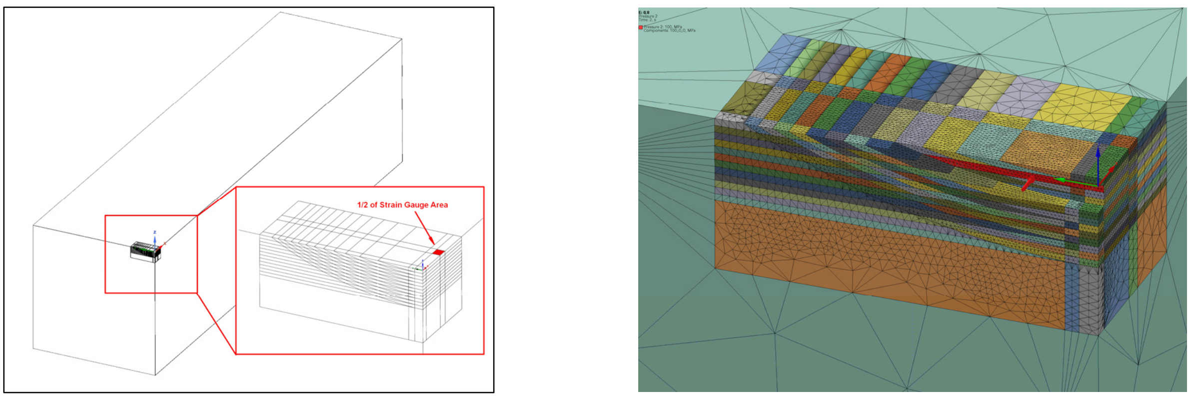
To reduce the high dispersion of evaluated stress due to ill-conditioned matrix $\bar{\boldsymbol{a}}$, the tri-diagonal matrix **c** is used, implementing Tichonov second derivative regularization. The factor α controls the amount of regularization

$$(\bar{\boldsymbol{a}}^T\boldsymbol{a} + \alpha c^T\boldsymbol{c})\boldsymbol{\sigma} = E\bar{\boldsymbol{a}}^T\boldsymbol{\varepsilon} \quad (3)$$

FEM analysis. Numerical values of calibration constants were calculated for given grinding wheel diameter, for strain gauge HBM 0.6LY11 grid dimensions and for given distance of the strain gauge from the groove edge. FEM analysis was made inside system ANSYS v 19.1. Used type of elements is quadratic TETRA. Specimen was cut on 1/8 of real test specimen to reduce number of elements and to simplify of boundary conditions. The loading was considered as stress 1 MPa in each layer of thickness 0.2 mm for each of 12 depth of grinding. Average stresses in place of strain gauge are evaluated in to triangular matrix $\bar{\boldsymbol{a}}$. Here corresponding member a_{jk} of matrix $\bar{\boldsymbol{a}}$ is average stress on area of strain gauge $S_{StrainGaugeArea}$.

$$a_{jk} = \{\textstyle\int \sigma_{x,jk} dS\}/\{S_{StrainGaugeArea}\} \quad (4)$$

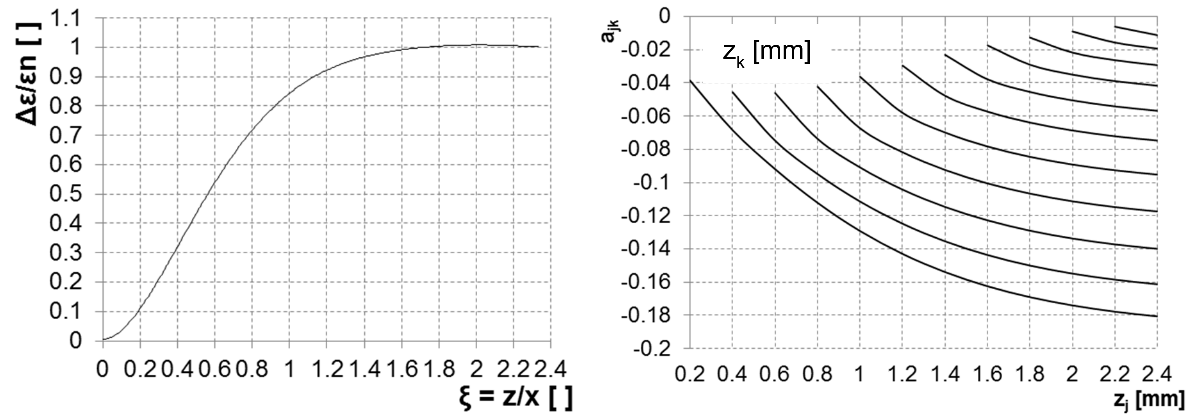
The FEM model was made with fine mesh in relevant surrounding of strain gauge and grinding disk, see Fig. 2 The calibration constants were derived as for homogenous as for non-homogenous stress profile.



a) b)

Fig. 2: Geometry of 1/8 test specimen, position of strain gauge area (a) and FEM model with forth drilled depth and introduced stress in the second upper removed layer (b)

The relieved strain related to the homogenous nominal strain ε_n for dimensionless grove depth ξ, given as the ratio of the depth and the distance of the strain gauge centre from the groove edge, is presented in the Fig. 3a. The triangular matrix of calibration constants for non-homogenous stress profile is schematically given in Fig. 3b expressed as the curves for partial depths.

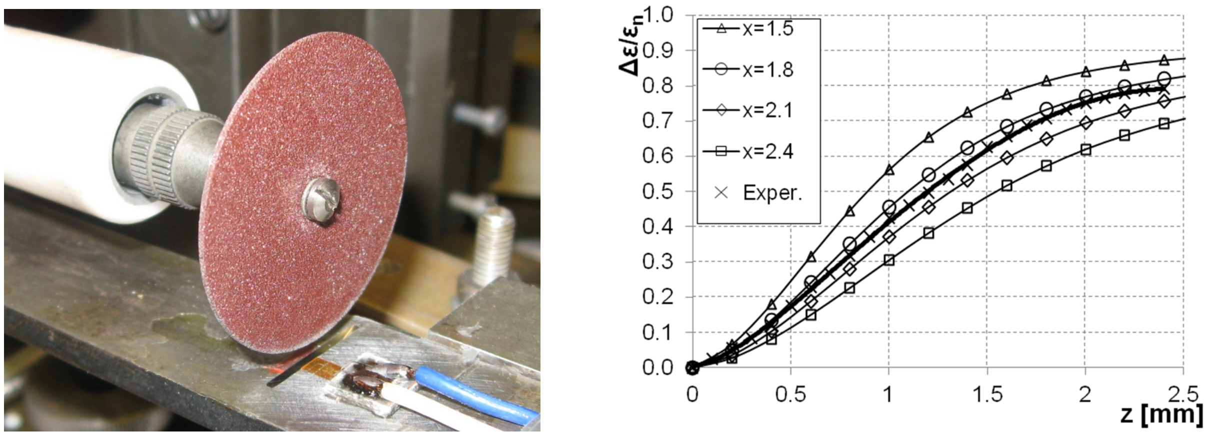


a) **b)**

Fig. 3: Calibration coefficients for homogenous and non-homogenous residual stress profile

Implementation

Calibration constants for homogenous stress profile were verified experimentally by tension and bending tests. The bending test was performed on the rectangular beam on tension upper side (Fig. 4a). The resulting strain relaxation obtained experimentally (x = 2) was compared with the relaxation curves, obtained using FEM analysis for various distances of the strain gauge centre x from the groove edge. It is obvious, that the experiment fits to the calculated curves very well.



a) b)

Fig. 4: Verification of calculated calibration constants with bending test

A handy grinding tool has been developed for in-situ tests (Fig. 5). The measurement of longitudinal residual stress in forged bar, used for the manufacture of LP turbine blades is demonstrated in next text. Residual stress is presented in forgings of some producers, which causes the deformations of blades after their milling. Two SG were used, 2 mm and 4 mm from the groove edge, considering that the change of released strains in larger depths is greater at the second strain gauge. Evaluated stresses are presented in Fig. 6b. Two bottom lines represent the stress, evaluated for homogenous stress field. Unfortunately using this access, the evaluated stresses at larger depths are influenced from high stresses at the surface and are evaluated not properly (the residual stresses are compressive for all depths). The real residual stresses are given from the upper diamond filled curve, which represents the stress, calculated with integral method from the first strain gauge positioned just at the grooved edge. It is obvious, that below 0.3 mm depth the residual stresses are tensile. The crosshair curve represents the stresses, evaluated using integral method from released strain at the second strain gauge, positioned 4 mm from the groove edge. It is visible, that the evaluated stresses are not representative near the surface, but the dispersion of stresses is lower in the depths, approaching the depth of 2 mm. The last upper curve represents the longitudinal stress, measured using hole-drilling method and evaluated also using integral method. This curve fit very well with the stresses, obtained with grinding groove method, evaluated with integral method.

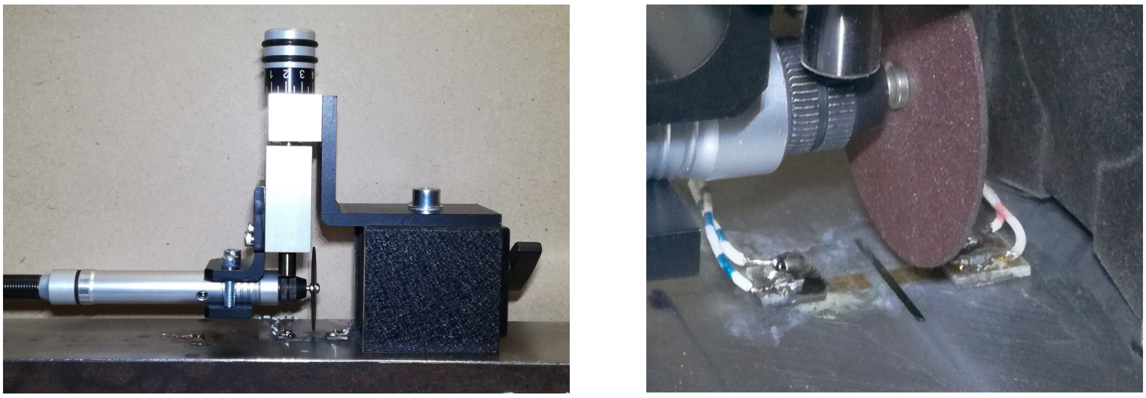


Fig. 5: Tool for measurement residual stresses using groove grinding method (a) and detail of the positions of the relieved strain measuring two strain gauges (right 2 mm and the left 4 mm from the groove edge)

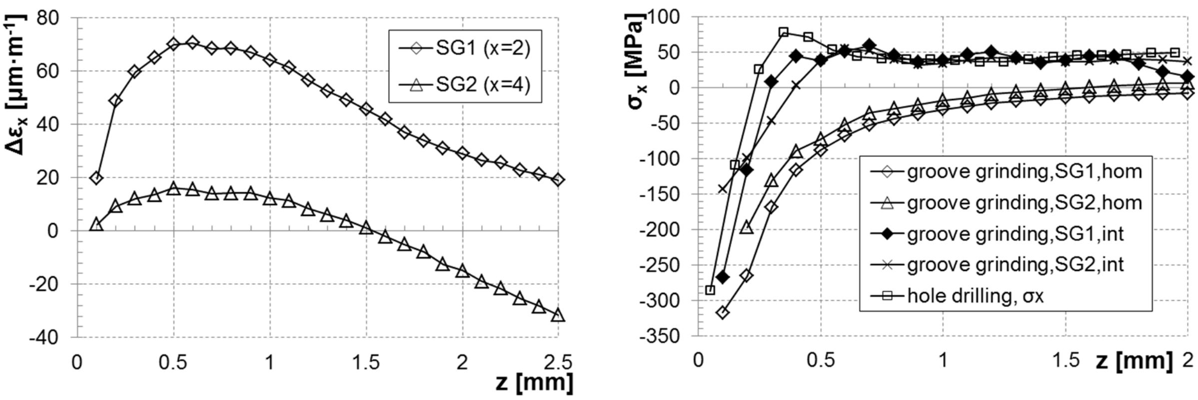


Fig. 6: Measured relieved strains at strain gauges (a) and evaluated residual stress profile (b)

Conclusions

Proposed method is very well suited for stress profile measurement of single stress component, is easier in comparison with hole-drilling method, portable and has good repeatability. Multi-cuts can be performed for multi stress components.

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References

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