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Experimental Stress Analysis

COMPARATIVE STUDY OF EXPERIMENTAL METHODS FOR EVALUATION OF RESIDUAL STRESS DISTRIBUTION

Kamil Kolařík[1], Nikolaj Ganev[2], Zdenek Pala[3] & Totka Bakalova[4]

Abstract: The aim of the contribution is to present the experience of the X-ray diffraction laboratory of the Czech TU in Prague with residual stress analysis of steel surfaces after mechanical machining by using three methods for residual stress determination. Besides X-ray diffraction, hole-drilling and layer-removal experimental techniques were applied for residual stress depth profiling after milling, grinding and scraping of steel guide gibs. The main goal of research is to assess applicability of tested methods in the case of a shallow state of macroscopic residual stresses.

1. Introduction

Recently there is an increasing interest in how the state of residual stress (RS) affects the mechanical properties of a material and machine parts. The failure of a structure or a mechanical component is not only due to externally applied loading. Residual stress is an important parameter in this respect. All manufacturing processes introduce a new state of residual stress. These stresses can have a positive effect, such as increasing the fatigue limit in the case of compressive surface stress, or they can have a negative effect e.g. decreasing the stress corrosion resistance of a material with tensile residual stresses.

Basic and applied research in the field of residual stress has been accelerated in the last few years. Residual stresses are taken into account in advanced design in the aerospace, automotive and nuclear industries. In order to satisfy industrial and scientific needs, considerable progress has been made in experimental techniques for residual stress measuring. Today these methods are widely used not only for research and development but also for quality control.

2. Residual Stress Measuring Techniques

Nowadays there are various qualitative and quantitative methods for residual stress analysis based on a relation between the residual stress and a specific characteristic of the investigated object. In general, they are classified as destructive and non-destructive techniques [1, 2].

[1] Ing. Kamil Kolařík, Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Trojanova 13, 120 00 Prague 2, Czech Republic, kamil.kolarik@email.cz
[2] Doc. Ing. Nikolaj Ganev, CSc., Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague Trojanova 13, 120 00 Prague 2, Czech Republic, ganev@troja.fjfi.cvut.cz
[3] Ing. Zdenek Pala, Department of Solid State Engineering, Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague, Trojanova 13, 120 00 Prague 2, Czech republic, zdenek.pala@cvut.fjfi.cz
[4] Ing. Totka Bakalova, Department of machining and Assembly, Faculty of Mechanical Engineering, TUL of Liberec, Studentská 2, 461 17 Liberec 1, Czech Republic, tbakalova@seznam.cz

2.1. Destructive methods

The first category of methods is based on destruction of the force and momentum equilibrium in a mechanical component. In this way, the residual stress is measured by relaxing it. However, it is only possible to measure the consequences of the stress relaxation and not the relaxation itself. The hole-drilling technique and the layer removal technique rank among the most extensively used destructive methods both in research and industry practice.

The hole-drilling method involves localized removal of stressed material and measurement of strain relief in the adjacent material. The technique requires drilling a small hole, typically 1 – 4 mm in diameter, to a depth approximately equal to its diameter. A specialized three-element stain gauge rosette measures the surface strain relief in the material around the outside of the hole. Residual stresses existing in the material before hole drilling can be calculated from the measured relieved strains.

The layer removal method is based on the principle that a plane sample which contains residual stresses is deformed in such as way as to maintain the static equilibrium of the internal moments and forces. If the layers of such a material are gradually removed by chemical machining, the balance of internal stresses and moments is disrupted at the same time. To re-establish this balance, the part has to change shape. On a thin beam shaped test specimens this deformation is represented by its deflection. Calculation of residual stress depth profile is based on the deflection course and on the following presumtions:

- The prestressed test specimen is homogeneous and isotropic; its axes coincide with those of the principle stresses.
- The stress in the direction of thickness is negligible, i.e. only plane (biaxial) state of residual stress is assumed.
- The transverse stresses are considered negligible although they are usually not and thus should be taken into account.

2.2. Nondestructive methods

The second series of techniques consist of nondestuctive methods. These are based on the relationship between the physical or crystallographic parameters and the residual stress. The most frequently used non-destructive techniques are: the X-ray diffraction method, the neutron diffraction method, the ultrasonic method and the magnetic method.

The principle of the X-ray diffraction and neutron diffraction methods rests in the measurements of lattice strains by studying the variations of the interplanar spacing of the polycrystalline materials. Since the first method measures the residual strain on the surface of the material, the second measures the residual stress within a volume of the sample. The diffraction techniques can be used to study both the macroscopic and microscopic residual stresses.

Ultrasonic techniques for the measurement of stress are based on variations in the velocity of ultrasonic waves, which can be related to the state of residual stress through the third order elastic constants.

Magnetic stress measuring methods rely on the interaction between magnetization and elastic strain in ferromagnetic materials.

The ultrasonic and magnetic methods are sensitive to all three kinds of residual stress, but cannot distinguish between them.

3. Samples under Investigation

Three types of machined surface layers for guide gibs were examined. Samples from the steel 11 375.0 were prepared by milling (A), grinding (B), and scraping (C). Semiproducts were cut from the steel sheet without any heat treatment by using an acetylene jig-burner.

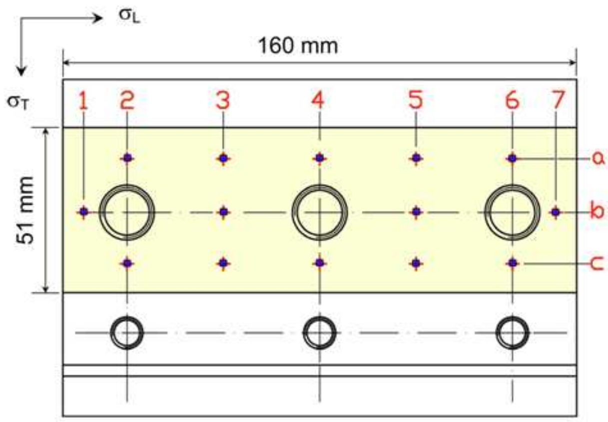

Figure 1: *Scheme of the measured surface 160 × 51 mm^2 on samples with marked directions of stress determination σ_L, σ_T and the grid of measured points.*

4. Experimental Techniques

Three different experimental methods for residual stress determination were applied.

4.1. X-Ray diffraction (XRD)

The measurements were performed on an θ/θ goniometer X´Pert PRO with CrKα radiation. The diffraction line *{211}* of α-Fe phase was analysed. The $\sin^2\psi$ method [2] with nine different tilt angles ψ was used. The X-ray elastic constants $½s_2$ = 5.76•10-6 MPa^{-1}, $-s_1$ = 1.25•10^{-6} MPa^{-1} were used in macroscopic stress calculations. Depth profiles of X-ray diffraction characteristics were obtained by surface layers removal with a LectroPol–5 device for electrolytic polishing.

4.2. Layer removal method (LRM)

Beam shaped specimens were prepared from the investigated samples in order to apply the layer removal method (LRM) for determination of RS depth profiles. In the experimental arrangement the one end of the measured specimens is fixed, while the other is unbound. While a well-defined area on the surface is being continuously and uniformly electrochemically dissolved, the detection system on the free end of the sample registers its deflection. Using the theory of elasticity, a depth profile of stress can be calculated from the course of measured deformation.

4.3. Hole-drilling method (HDM)

Hole-drilling method [3] was performed using drilling device MTS 3000 SINT-RESTAN. Tensometric rosettes 1.5/ 120RY61S made by HBM were used for experimental measurement of residual stress. The rosettes were arranged in halfbridge set-up. Shell end milling cutter was 1.8 mm in diameter, the speed was 300 000 RPM and step of drilling was 0,020 mm.

The measured released deformations were approximated by a polynomial of 4. – 5. kind, the data evaluation was done employing calibration coefficients which were obtained numerically by integral method [3]. The minimal and maximal depths for data treatment were in this case approximately 50 μm and 0.6 mm respectively.

5. Results and Their Discussion

5.1. X-ray diffraction method

The macroscopic residual stress depth profiles obtained by X-ray diffraction analysis (XRD) are shown in Figures 2 – 4.

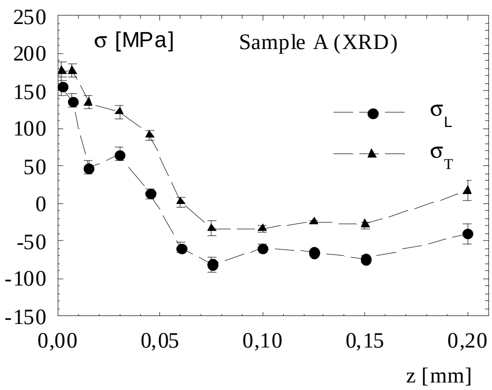

Figure 2: *Depth profiles of RS σ_L and σ_T obtained for the milled sample A.*

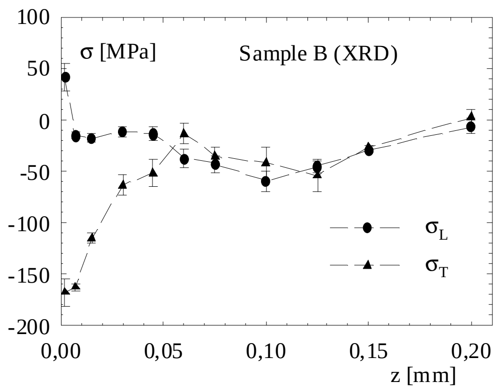

Figure 3: *Depth profiles of RS σ_L and σ_T obtained for the milled sample B.*

It is evident that each machined layer has distinctive character of surface macroscopic residual stresses (RS) and their depth distribution. While (i) milled specimen exhibits tensile RS and (ii) scraped surface compressive RS on the surface in both measured directions, (iii) the ground surface is characterized by anisotropic state of RS with relatively low tensile RS in the grinding direction and compressive RS in direction perpendicular to grinding.

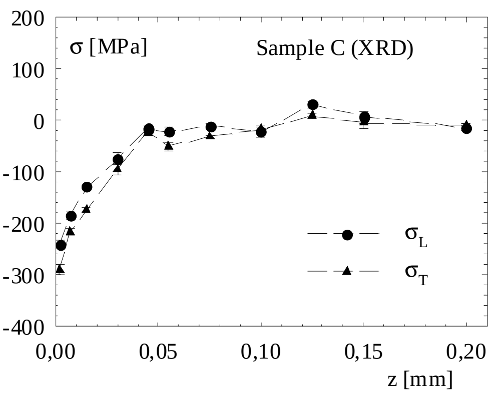

Figure 4: *Depth profiles of RS σ_L and σ_T obtained for the milled sample C.*

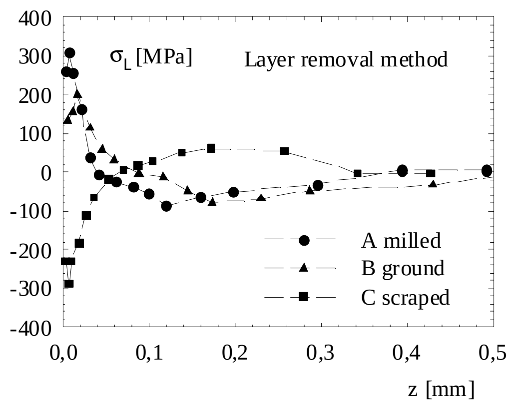

Figure 5: *Courses of RS σ_L and σ_T obtained for the analyzed samples by using LRM.*

5.2. Layer removal method

Figure 5 contains all three courses of residual stress measured by the destructive technique of continuous electrochemical dissolving in longitudinal direction of prepared specimens.

Comparing results plotted in Figures 2 – 4 with those in Figure 5 it could be seen that in the case of samples A and C the residual stress values obtained by both the applied methods are in a good agreement. Despite of complexity of the anisotropic RS state after grinding the depth profiles show qualitative correspondence of longitudinal stresses σ_L measured in sample B by XRD and LRM.

5.3. Hole-drilling method

Principal residual stresses evaluated from hole-drilling method measurements are presented in Figures 6 – 8.

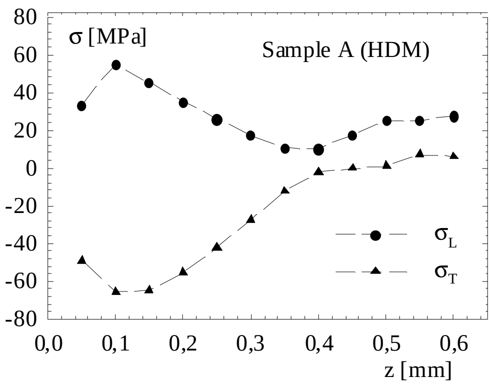

Figure 6: *Depth profiles of RS σ_L and σ_T obtained for the milled sample A.*

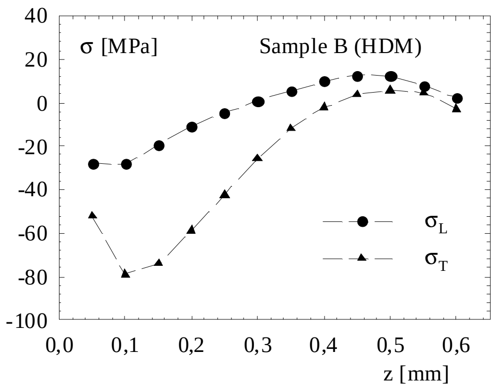

Figure 7: *Depth profiles of RS σ_L and σ_T obtained for the milled sample B.*

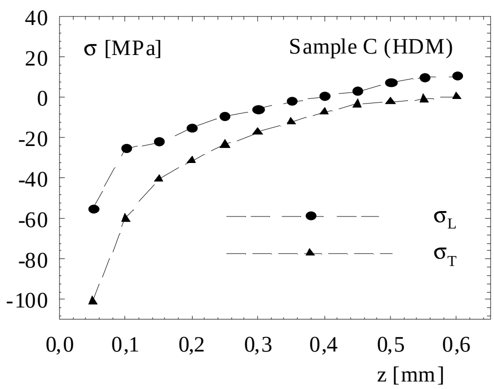

Figure 8: *Depth profiles of RS σ_L and σ_T obtained for the milled sample C.*

6. Conclusions

Comparing the applied measuring techniques we should be aware of the fact that they are based on different principles, and therefore they are not interchangeable. Considering that no experimental method determines stress but only deformation or another stress-dependent magnitude, it is evident that the correct interpretation of experimental data requires comprehension of the measuring conditions and the ground of experimental procedures.

Comparative RS study proved the particular status of X-ray diffraction technique which enables local non-destructive evaluation of surface stresses, essential to estimate fatigue life of machine parts. Furthermore, measurements can be performed in various directions on the sample's surface. Using a layer removing it is possible to obtain a depth profile of stresses.

Layer removal method gives reasonable results in the case of isotropic prestressed planar states of residual stress.

The hole-drilling technique is limited by emergence of plastic deformation and thus of a detectable stress relief in the hole's vicinity. Therefore the method becomes effective from depths bigger than 50 – 100 μm.

No universal technique which will solve every problem, but by judicious combining the means at our disposal, most research and industrial needs can be met.

Acknowledgements

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