ANYAGVIZSGÁLÓK LAPJA Elektronikus folyóirat
MINŐSÉGBIZTOSÍTÁS * ÁLLAPOTELLENŐRZÉS 2008/2

Enhancement of X-Ray Diffraction Measurement of Residual Stresses by Using of Area Position Sensitive Detector

Maradó feszültség meghatározása rötgen-diffrakciós eljárással, terület-érzékeny mérőfej alkalmazásával

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Keywords: *Residual stress, X-ray diffraction, Area detectors, Imaging plate*
Kulcsszavak: *maradó feszültség, röntgen diffrakció, területi detektor, kép lemez*

Összefoglalás

Gépalkatrészek megbízhatóságának, élettartamának növelésének igénye - úgy a járműipar, légi közlekedés járművei, mint a nukleáris berendezések területén - szoros kapcsolatban áll a technológiai, gyártási eljárásokkal, valamint az alkatrészek végső megmunkálási paramétereivel. A felszíni rétegek egyik legfontosabb jellemzője a maradó feszültség. Amennyiben ismerjük a maradó feszültségek mértékét, lehetőségünk adódik olyan felületkezelések alkalmazására, amelyek eredménye nyomó feszültség kialakulása a szélső szálakban. A röntgen diffrakciós mérési eljárás fémes szerkezetek, valamint kerámiák esetén lehetőséget biztosít a maradó feszültségek meghatározására. A dolgozat egy repülőgép-ipari alkalmazás kapcsán mutatja be egy, területre érzékeny mérőfej elrendezés alkalmazását a maradó feszültségek meghatározásában.

Abstract

The growing requirements for reliability and life of machine components, in particular in automotive and aeronautics industries, as well as in nuclear power-plant engineering are closely related to technological procedures in manufacturing and final treatment. Residual stresses (RS) are one of the most important attributes of surface layers. If the residual stresses are known, it will be possible to predict operational reliability of mechanical parts and to choose such surface treatment that would result in creating a compressive pre-stressed layer acting as a barrier to prevent crack propagation into the material. X-ray diffraction methods represent a well developed tool for investigation of residual stress fields in metallic materials and engineering ceramics. The aim of this contribution is to present the enhanced arrangement of X-ray diffraction technique equipped with an area sensitive position detector and to illustrate its capabilities when applied in aircraft industry.

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Introduction

From the point of view of limiting values of stiffness, strength and life, surface of the machine components is the critical place. It is a known fact that operating reliability of machine parts is often determined more by the way their surface is finished rather than by the specific material composition. The growing requirements for reliability and life of machine components, in particular in automotive and aeronautics industries, as well as in nuclear power-plant engineering are closely related to technological procedures in manufacturing and final treatment. New high-strength materials and high rates of reduction during final surface creation raise misgivings about a favourable impact of the great energy put in the surface on functional properties of machine parts.

Residual stresses (RS) are one of the most important attributes of surface layers. They are formed in bodies of random composition as a result of the acting of external forces, thermal fields, phase transformations, etc., either directly or indirectly, as a result of inhomogeneous deformation, e.g. during the already mentioned surface finishing of machine parts and structures. If the residual stresses are known, it will be possible to predict operational reliability of mechanical parts and to choose such surface treatment that would result in creating a compressive pre-stressed layer acting as a barrier to prevent crack propagation into the material. Therefore, analysing residual stresses as part of material diagnostics is of the same importance as classic material testing methods, such as determining strength, impact hardness, hardness, resistance to abrasion and corrosion, etc.

X-ray diffraction methods represent a well developed tool for investigation of residual stress fields in metallic materials and engineering ceramics [1]. Due to the limitations of X-ray penetration depth, the X-ray diffraction technique can be used only for surface layers few micrometers in thickness. In the case of conventional X-ray diffraction equipment, investigation of stress depth profiles is performed in combination with electrochemical etching.

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Designing safe structures, which make full use of the material properties without inappropriate reserves, requires more than simply establishing the existence of a surface layer with excessive compression or tensile stresses. It is essential to know the lateral distribution of surface residual stresses, which in principle may not be homogeneous. Knowledge of any changes in the material structure and properties of the surface layer is equally important. The X-ray diffraction analysis is a reliable method of obtaining this information.

The aim of this contribution is to present the enhanced arrangement of X-ray diffraction technique equipped with an area sensitive position detector and to illustrate its capabilities when applied in aircraft industry.

X-ray diffraction stress measurement

The X-ray diffraction technique of residual stress measurement is based on accurate determination of crystallographic lattice strains and their conversion to stresses using theoretical elasticity equations. The method makes use of the fact that X-rays are diffracted by crystal lattices. Their strains are determined from the changes of reflected atomic planes depending on the applied mechanical stress.

When the sample dimensions or shape do not allow applying the classic "sin²ψ" method with an ω – or ψ – goniometer for X-ray diffraction stress determination, it is possible to use the *single-exposure (one-tilt) method without reference substance* (Fig. 1), which is a special case of the "sin²ψ" method [1, 2]. This experimental arrangement is very useful for industrial investigations.
If in this experimental arrangement the angle of incidence of the X-ray beam on the surface of the sample is $\psi_0 = 45°$, then the surface stress $\sigma_1 = \sigma_\varphi$ can be written as

$$\sigma_\varphi = \frac{1}{\frac{1}{2}s_2}\,\frac{\operatorname{cotg}\theta.\cos^2 2\theta}{2D}\,\frac{\Delta^{hkl}}{\sin 2\eta}, \qquad (1)$$

where θ is the Bragg's angle, η = 90° – θ, D – the distance between the film and the sample, $\Delta^{hkl} = r_{\psi_1} - r_{\psi_2}$ is the eccentricity of the diffraction ring (Fig. 1).
Equation (1) could be rewritten as

$$\sigma_\varphi = \frac{1}{\frac{1}{2}s_2}\,\frac{1}{A}\,\Delta^{hkl}, \qquad (1a)$$

then

$$A = \frac{2D.\sin 2\eta}{\operatorname{cotg}\theta.\cos^2 2\theta}$$

remains constant during the experiment.

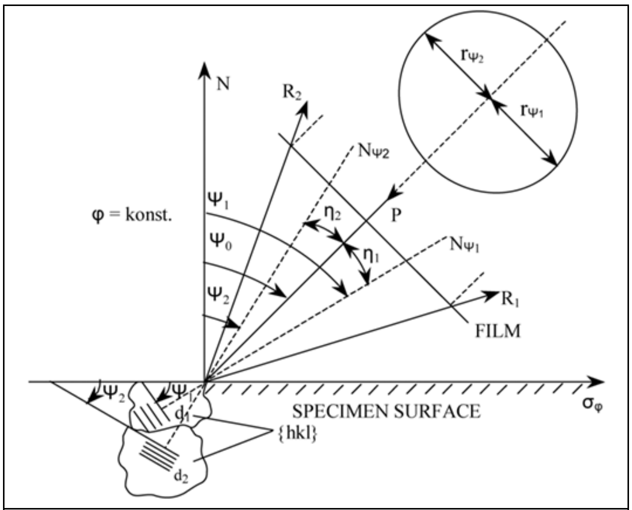

Fig. 1 Principle of the single-exposure method without reference substance
1. ábra Az egyszeres expozíciós módszer referencia minta nélkül

Enhanced experimental arrangement of the one-tilt method

Originally a conventional X-ray film was used for detection of diffracted radiation. After darkroom processing consisting in developing, fixing, and drying of the film, diffraction patterns on photographic emulsion were evaluated by using a microdensitometer with digital record of the density of blackening.
Recently the plastic sheet coated with europium-activated halides (imaging plate (IP) detectors) has become one of the popular area detectors in modern diffraction experiments owing to its high sensitivity, high spatial resolution, and more comfortable processing in comparison to the photographic emulsion.
A schematic drawing of the measuring chain is shown in Fig. 2. The incident beam of cross-section 0.5 – 2.0 mm in diameter generated in the X-ray tube (1) impinges the measured sample (2) placed on the table (3). The backscattering Debye – Scherrer diffraction line is detected by means of a *Duerr* imaging plate [3] area detector (4) instead of a photographic film. The sensitive layer in the imaging plate comprises a barium chromo-bromide luminophore, which is excited by an incident X-ray photon into a metastable state. This excited state is then harmonically released by a He-Ne laser, and thus the photostimulated luminescence is triggered and a 16-bit greyscale image is produced. The process of photostimulated luminescence is performed in the scanner (5) *VistaScan* by *Duerr* and the phosphor image is then transferred digitally to a computer. The diffraction line profile is gained from the 16-bit greyscale pattern by using the *Lucia v. 5.10* image analysis system (6) and

crystallographic lattice deformations are then evaluated [3]. After that, the image information is erased by means of UV light (7) and the detector (imaging plate) is prepared for a new measurement.

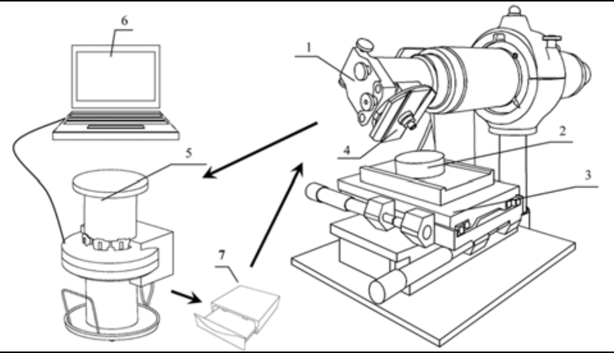

Fig. 2 Schematic drawing of the measuring set
2. ábra Mérőelrendezés sematikus ábrája

Investigation of lateral RS heterogeneity on turned surfaces

The modernized arrangement of the "one-tilt" method with no reference substance [2] was applied to investigate the distribution of residual stresses on ***turned surfaces of the piston rod made of commercial steel L-ROL (Fe-0.32C-1.0 Mn-1.1Si-1.0Cr-0.3Ni-0.25C used in aircraft industry***. The incident CrKα beam directed by a cylindrical collimator of 1.7 mm in diameter reached the sample surface at an angle of $\psi_0 = 45°$ in the longitudinal and transversal direction, in which the surface components of axial σ_a and radial σ_r, stresses respectively, were analyzed (Fig. 3).

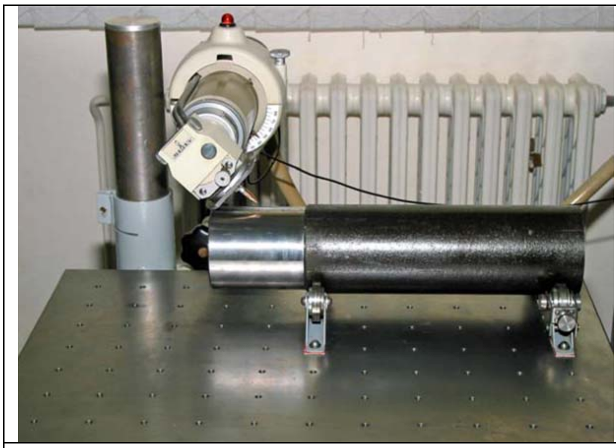

Fig. 3 Measurement of axial residual stresses σ_a on the turned surface of investigated samples
3. ábra Az axiális visszamaradó feszültség mérése a minta esztergált felületén

The record of the {211} α-Fe diffraction line intensity curve was obtained from a position sensitive detector based on imaging plates (Fig. 4). The X-ray elastic constant $½s_2 = 5.76 \cdot 10^{-6}\ N^{-1}m^2$ was used in residual stress calculations [1]. In addition to macroscopic residual stresses, the width W of diffraction line {211} α-Fe was evaluated from the diffraction pattern. This quantity represents the degree of plastic deformation in the surface layer due to the mechanical treatment.

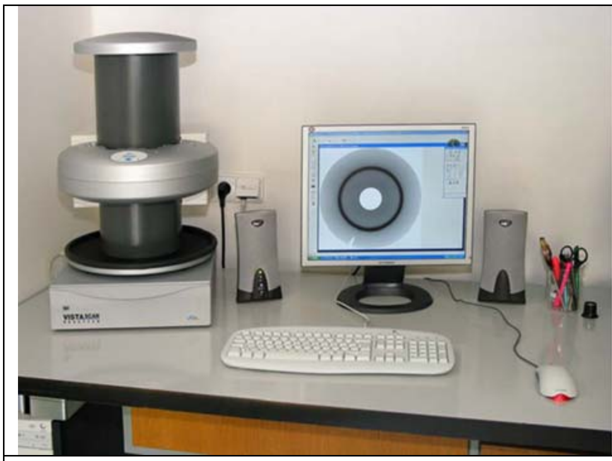

Fig. 4 Workplace for processing of imaging plate and for digital evaluating of diffraction patterns
4. ábra Munkaállomás a képfeldolgozáshoz és a diffrakciós vonalak digitális kiértékeléséhez

During X-ray diffraction monitoring of the manufacturing process an area of significantly inhomogeneous residual stresses depending on turning was found. The region was subject to a detailed examination of lateral distribution of surface residual stresses. A set of seven equidistant measuring points A, A1, …, A6 was chosen on the investigated surface (Fig. 5).

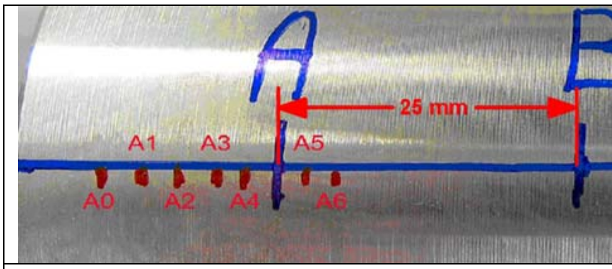

Fig. 5 Position of the measured places A0, A1, …, A6 placed along the line parallel to the axis of the cylindrical sample. The distance between two neighbouring points is ca. 3 mm
5. ábra A0, A1 ....A6 helyek a hengeres minta axiális tengelyének irányában. A két szomszédos pont távolsága kb. 3 mm

The obtained local non-uniformity of RS (Tab. 1, Fig. 6) indicates the existence of structure heterogeneity in the sample.

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Tab. 1 Values of surface residual stresses (MPa) obtained on the analyzed surface in longitudinal ($\square_a$) and transversal ($\square_r$) direction. The experimental inaccuracy was approx. 50 MPa.

Place	A0	A1	A2	A3	A4	A	A5	A6
$\square_a$	–	432	150	32	-95	71	295	466
$\square_r$	408	356	256	320	231	208	387	476

Conclusions

- The detection of diffracted X-rays by means of an imaging plate is timesaving in comparison with the lengthy conventional film processing. Another advantage is the possibility of direct numerical evaluating of diffraction patterns which enables to reach the accuracy in stress determination comparable with difractometer analysis.
- The identification of non-uniformity of residual stresses (Fig. 6) on the turned surface of the piston rod used in aircraft industry demonstrates the capability of the enhanced experimental set (Fig. 2).
- The obtained lateral gradients of residual stresses reached values of approx. 100 MPa·mm^{-1} and thus give evidence about structure inhomogeneity in the surface layer. Taking into account that the residual stresses in question are tensile with one exception (Tab. 1), the obtained information could contribute to preventing the harmful impact of RS on operational reliability of critical aircraft machine components.

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