A PORTABLE X-RAY APPARATUS FOR BOTH STRESS MEASUREMENT AND PHASE ANALYSIS UNDER FIELD CONDITIONS.

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ABSTRACT

The wide range of possible applications for the portable X-ray apparatus with an air cooled double-anode X-ray tube are presented. The apparatus is provided with a stress measurement unit and focusing camera for phase analysis. The distinctive characteristics of the apparatus are a small weight (≈ 4 kg), fine focus ray tube, portability and ease of use for both laboratory samples and industrial components. In the present paper the technical characteristics of the equipment, the methodology and experimental results are described. The most important of these are the following: measurements of tensile force in pre-stressed steel cables in concrete, residual stress measurements in railway wheels, stress measurements at elevated (up to 300^0C) temperatures and stress measurements in welded joints including stresses in the weld bead and heat affected zone.

INTRODUCTION

A portable X-ray apparatus offers a wide range of possibilities for use in the non-destructive control of stresses in structures and components. Moreover, they permit the user to carry out in-service control of different technological processes or the stress state of industrial equipment. Information has been published regarding existing portable X-ray equipment [1,2], but, in our opinion, their portability does not fulfil the requirements for use under field conditions.
In the present paper an original design of a portable X-ray apparatus is presented. The methodology to carry out the measurements and some experimental results are described.

DESIGN AND TECHNICAL CHARACTERISTICS OF THE EQUIPMENT

The X-ray apparatus described is intended for both stress measurement and for phase analysis. A mounted position shown in fig. 1. Fig. 1a represents the apparatus mounted for stress measurements and fig. 1b demonstrates the configuration for the phase analysis focusing camera. The following units are included as components of the portable apparatus represented in fig. 1a and 1b.
1. Power and control unit which supplies a high voltage source, and permits adjustment of the anode current and voltage of the X-ray tube under operating conditions. The weight and size of the unit are 1.5 kg and (20x12x8) cm^3 respectively.
2. A high voltage source and X-ray tube. The distinctive design of this unit is that the X-ray tube is coupled to a high voltage source. The source body is cylindrical in form, has a 5 cm diameter and is 37 cm long. The X-ray tube, operated at 25 kV and 2 mA, has two air cooled anodes which emit the two convergent X-ray beams necessary to fulfil the two exposure technique for X-ray stress measurements. The convergence angle in this case is 50 degrees and may be selected by

collimator slits from 40 to 60 degrees. For carrying out a phase analysis only one of the two beams is used. The weight of the high voltage source with X-ray tube is 2.5 kg.

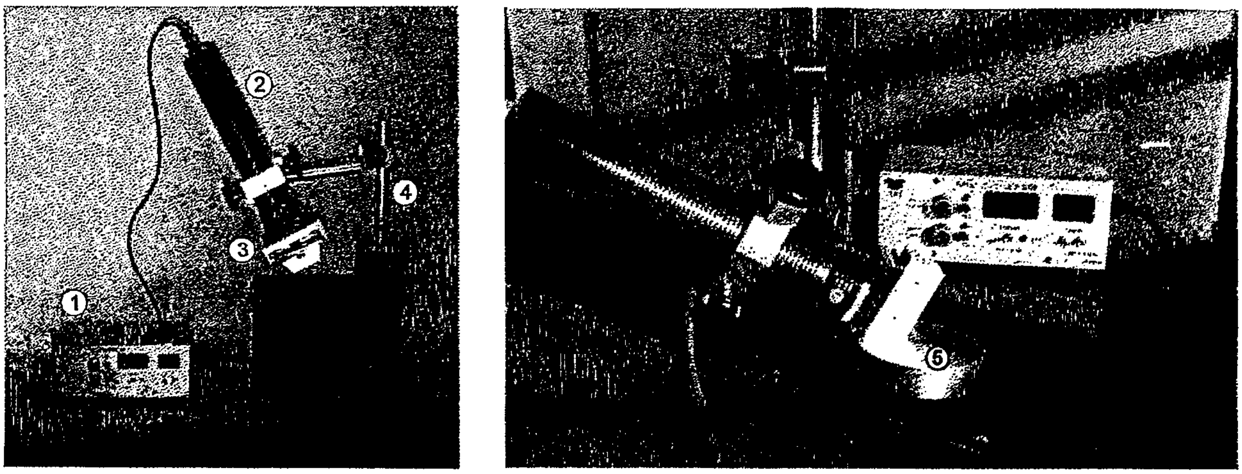
3. A magnetic support allows the apparatus to be attached to any ferromagnetic plate, or directly to the metal object to be tested. It also enables the adjustment of the X-ray source in the exposure position.

4. A collimator unit with film cassette for stress measurement (see fig. 1a). Two cassette windows provide collection of diffraction lines in 2θ angular intervals from 148 to 164 degrees.

5. A focusing camera for phase analysis (see fig.1b). The diameter of the camera based on Seemann-Bohlin focusing is 104 mm and the apparatus is capable of measuring 2θ diffraction lines from 35 to 155 degrees.

In the present model of the portable X-ray apparatus film measuring is used both for stress measurement and phase analysis. Film measuring gives lighter weight equipment and simplifies the apparatus design.

To maintain the accuracy of measurements at a high level, the film reading is carried out by computer-controlled microdensitometer and the data processing is completely computerised. Line position is determined by approximating the profiles with a double Cauchy function. The coefficients of the Cauchy function describing an experimental profile are simulated and solved by a regression method.



a b

Figure 1. Portable apparatus for stress measurements (a) and for the phase analysis (b).
1-power and control unit; 2-high voltage source; 3-collimator with film cassette;
4-magnetic support; 5-focusing camera.

STRESS MEASUREMENT METHODOLOGY

The principals of the double exposure technique used in stress measurements using the described portable equipment, are based on the determination of two strain components $\varepsilon_{\varphi,\psi 1}$ and $\varepsilon_{\varphi,\psi 2}$ [3]. If the strain $\varepsilon_{\varphi,\psi}$ is expressed by the formula:

$$\varepsilon_{\varphi,\psi} = \frac{1+\nu}{E}\sigma_\varphi \cdot \sin^2\psi - \frac{\nu}{E}(\sigma_1 + \sigma_2), \qquad (1)$$

then the difference between the two strain components is

$$\varepsilon_{\varphi,\psi_2} - \varepsilon_{\varphi,\psi_1} = \frac{1+\nu}{E}\sigma_\varphi\left(\sin^2\psi_2 - \sin^2\psi_1\right), \qquad (2)$$

where E and ν are elastic constants of the material, ψ and φ - polar and azimuthal angles, σ_φ - a measured stress component, σ_1 and σ_2 - the principal stresses The stress component σ_φ from the expression (2) is equal to the following:

$$\sigma_\varphi = \frac{E}{1+\nu} \frac{\varepsilon_{\varphi,\psi_2} - \varepsilon_{\varphi,\psi_1}}{\sin^2\psi_2 - \sin^2\psi_1}, \qquad (3)$$

Using differentiation of Bragg's law:

$$\varepsilon_{\varphi,\psi} = \frac{d_{\varphi,\psi} - d_0}{d_0} = -\mathrm{ctg}\theta_0(\theta_{\varphi,\psi} - \theta_0), \qquad (4)$$

where $d_{\psi,\varphi}$, d_0 and $\theta_{\psi,\varphi}$, θ_0 are the interplanar distances and the diffraction angles of stressed and unstressed material respectively.

From expressions (3) and (4) the final formula for the determination of the σ_φ stress component may be obtained as

$$\sigma_\varphi = -\frac{E}{1+\nu} \frac{\mathrm{ctg}\theta_0(\theta_{\varphi,\psi_2} - \theta_{\varphi,\psi_1})}{\sin^2\psi_2 - \sin^2\psi_1}, \qquad (5)$$

Thus, to determine any stress component it is necessary to measure the diffraction angles corresponding to reflection from lattice planes with normals characterised by angles ψ_1 and ψ_2. The angular values used in the apparatus presented are $\psi_1=0^0$ and $\psi_2=50^0$ and "ψ - goniometer" geometry is applied to carry out the stress measurements. This geometry is shown in stereographic projection (fig. 2) that illustrates the angular position of two diffracted beams and location of two normals $\overrightarrow{n_{\psi 1}}$ and $\overrightarrow{n_{\psi 2}}$ to the diffracting planes. The projection also shows the location of the diffracted rings and their portions as registered on the film. The film cassette windows are also represented in stereographic projection.

A schematic diagram of stress measurements corresponding to this stereographic projection is shown in figure 3. Inclination of sample surface equal to 12^0 corresponds to measurement of steel sample using Cr-K_α radiation and (211) reflection with $\theta_{211} = 78^0$.

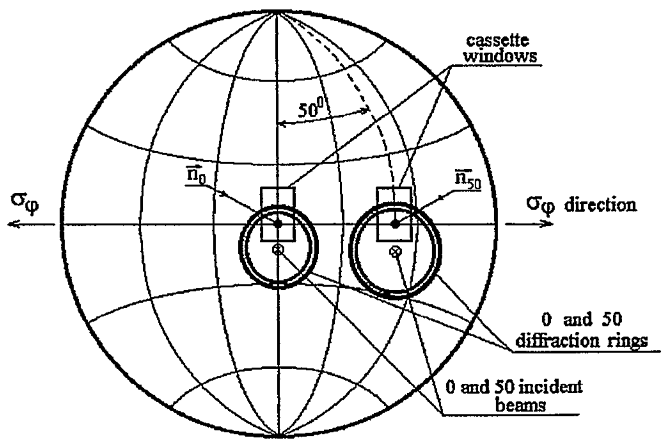


Figure 2. Stereographic projection of the ψ - goniometer geometry used in the portable X-ray apparatus.

As shown in figure 3, the perpendicularity of one of the incident beams to the x-axis means that angle ψ_1 is equal to 0 degrees and the value of ψ_2 in this case is equal to the convergence angle of two incident beams. For the X-ray apparatus, under discussion $\psi_2=50^0$.

Figure 3 also shows the principle of diffraction angle measurements. The angle difference $\Delta\theta = \theta_{\psi2} - \theta_{\psi1}$ in the equation (5) can be expressed as:

$$\Delta\theta = K(L_{50} - L_0), \quad (6)$$

where L_{50} and L_0 are the distances from the diffraction lines to a reference mark, and K is the scale and transfer coefficient from linear units to angle units.

The value of the coefficient K is a characteristic of the cassette - collimator unit and is determined from a calibration exposure of unstressed material. It is necessary to measure the distances between at least two lines with known values of diffaction angles or to use an interdoublet distance of standard material.

Substitution of expression (6) into equation (5) leads to the following formula for stress calculation:

$$\sigma = A(L_{50} - L_0), \quad (7)$$

where A is the constant including all known quantities entering into equation (5), such as elastic modulus and diffraction angle.

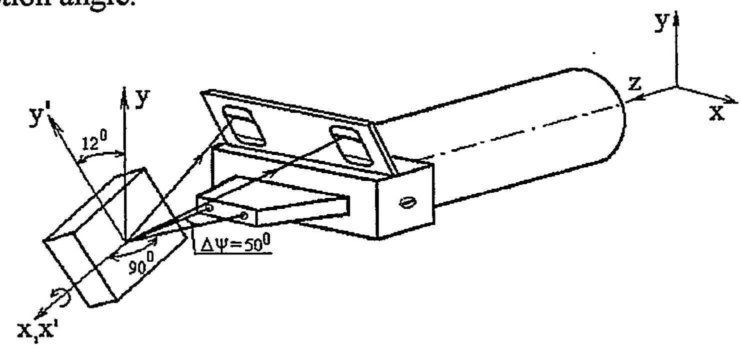


Figure 3. Scheme of stress measurements with portable X-ray apparatus.

METHODOLOGY OF PHASE ANALYSIS

The portable x-ray apparatus with focusing phase analysis camera is represented in figure 1b. The focusing method in this camera is the same as that applied to the Seemann-Bohlin camera. Figure 4 shows geometry of focusing and illustrates the data processing for the film to determine the diffraction angle values.

The position of the diffraction line in the schematic diagram (point B_1, for example) is characterised by the distance L from the incident beam point. The inclination angle of incident beam to surface plane is α (this angle is the camera constant). So:

$$\angle OAB_1 = \frac{\pi}{2} + \alpha - 2\theta, \quad (8)$$

The central angle formed by the arc L is equal L/r (r is the camera radio) and it is expressed as follows:

$$\frac{L}{r} = \pi - 2\left(\frac{\pi}{2} + \alpha - 2\theta\right) = 4\theta - 2\alpha, \quad (9)$$

From this expression:

$$2\theta = \frac{L}{2r} + \alpha = \frac{L}{d} + \alpha, \quad (10)$$

where d is diameter of the camera. In practice, it is impossible to measure line position on the film from the incidence point. Usually a reference is used to determine this position. If the position of the reference point is D (see fig. 4), and l_{ref} is the length of the arc AD, l_{mes} is a measured distance from reference to diffraction line then $L = l_{ref} + l_{mes}$. Formula (10) in this case transforms into:

$$2\theta = \frac{l_{ref} + l_{mes}}{d} + \alpha, \qquad (11)$$

or

$$2\theta = \frac{l_{mes}}{d} + \left(\frac{l_{ref}}{d} + \alpha\right), \qquad (12)$$

where l_{mes} is central angle corresponding the arc AD; introducing ω as $\omega = l_{ref} / d + \alpha$., the formula (6) transforms as

$$2\theta = \frac{l_{mes}}{d} + \omega, \qquad (13)$$

where ω is a new camera constant determined by a calibration exposure of a standard sample with known lattice parameter.

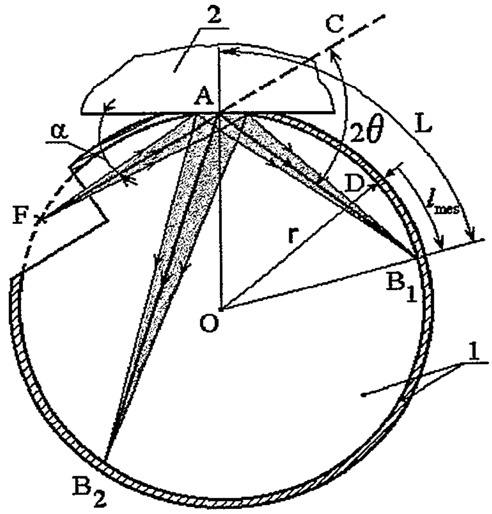


Figure 4.Schematic Diagram of the phase analysis camera.

Therefore, data processing of film in phase analysis is the same as in stress measurements and includes the reading of film by microdensitometer, determination of diffraction line position and phase analysis realised by lattice spacing data represented in ASTM standard cards.

EXPERIMENTAL RESULTS

Using the portable X-ray apparatus, numerous stress measurements were made under field conditions.

In a previous paper [4] the initial measurement of residual stresses in railway wheels were described. Later measurements showed that it is possible to use this X-ray apparatus in the nondestructive quality control of fabricated railway wheels. The criterion of quality is basically the existence of residual compressive stresses in the flange of the wheels. The presence of any residual tensile stresses characterises the component as out of specification in the fabrication of railway wheels.

Another example of an application of the portable apparatus regards the measurements of tensile force in the pre-stressed steel cables that are used in many building structures.

Two types of investigation were undertaken in this area. In the first, a comparison of the applied loading tensile force, acting on a cable consisting of 19 steel wire and the measured force calculated from stress measurements. The tensile force was calculated:

$$F = (\sigma \cdot A)n, \quad (14)$$

where A is the cross section of steel wire, n is the number of wires and σ is the measured stress value. The analysed cable has 19 wires and the diameter of each wire is 6 mm. The difference between applied and measured force, even in the case of a maximal load, that was equal to 10^5 kgf, did not exceed 10%. In other experiments, the same cables in a real building structure were analysed to investigate the relaxation process during service. The measured stresses acting in different wires and cables lie in interval from 800 MPa up to 1400 MPa and during at least three months of service examined stresses had remained practically unchanged.

Another application of the portable X-ray apparatus is the possibility to keep high precision stress measurements at elevated temperatures. In this kind of measurement it is possible to decrease the influence of thermal radiation by intensive air cooling. In spite of this, there is a thermal expansion of crystal lattice. The present X-ray apparatus using simultaneous registration of two reflections eliminates the influence of uncontrolled temperature variation of the surface. The measurements precision remains the some as in normal condition.

The portable X-ray apparatus also has been applied to measure residual stresses in welded joints, including weld beads and heat affected zones. Some results of these measurements have been published in recent paper [5].

CONCLUSION

The practical advantages of an X-ray apparatus have been presented. They consist in portability of apparatus due to coupling at high voltage source and air cooled double anode X-ray tube and in possibility to carry out of both stress measurements and phase analysis.

Simultaneous collection of two reflections permits high precision of stress measurements at elevated temperatures.

Stresses in weld beads and heat affected zones have been measured.

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