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DETERMINATION OF STRAIN IN MOVING OBJECTS BY X-RAY DIFFRACTION USING SYNCHROTRON RADIATION

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Determination of strain in moving objects by X-ray diffraction using synchrotron radiation

Dedicated to Ulrich Bonse on the occasion of his 60th birthday

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A novel method for the determination of strain in moving objects is presented. It is based on X-ray diffraction in parallel beam geometry. This geometry is not affected by errors of the sample position. Thus also moving objects can be investigated. Feasibility tests were made investigating the rotor blades of a turbo pump during rotation.

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Introduction

Most parts in machines, engines, etc. are subject to stresses as they move. Techniques used for strain measurements on static objects cannot be used for moving objects (for example acoustic methods) or only have model character (for example birefringence of light passing through a plastic model). Also conventional X-ray methods using focusing geometry fail, because the angles of diffraction are not measured directly but via the determination of the peak position on the detector circle (1). Displacements of the sample lead to errors in the peak location. Furthermore, deviations of the sample geometry from the ideal one and the finite penetration depth, especially in materials with low absorption leads to peak broadening.
Recently two new techniques using synchrotron radiation and parallel beam geometry for powder diffraction were introduced by Parrish et. al. (2) and Cox et. al. (3). The diffraction angle was determined either by using a set of parallel foils (Soller-collimator) (2) or an analyser crystal (3) for the collimation of the diffracted beam (Fig. 1). In both cases a parallel shift of the beam caused by a displacement of the sample does not affect the readings of the angle. So the measured values are correct as long as the diffracted beam fits into the analysing system. The range in which the sample is allowed to deviate from its proper position is thus only limited by the dimensions of the components of the analysing system. For our experiment we chose the set-up with an analyser crystal because of its higher resolution.

The experiment

Our measurements were made at the beamline F1 at HASYLAB. The beam from a bending magnet of the storage ring DORIS II was monochromatized by two germanium crystals in 111-orientation and parallel setting. The diffractometer consisted of two goniometers, one for the analyser crystal (germanium 111) and the detector and one for the sample, which were mounted independently from each other (4). The goniometer for the sample was mounted on a traverse and could be translated along its axis. In contrast to conventional diffractometers, where the goniometer for the sample is fixed on top of the one for the detecting system, this mounting

allows easy installation of arbitrary attachments without affecting the detecting system.

The analyser crystal and the detector were mounted in the same housing. The angle between a beam from the sample and the analyser as well as the angle between analyser and detector only depends on the wavelength and the lattice constant of the analyser. After adjustment in the primary beam (behind an absorber), which gave the zero position, the assembly could be rotated entirely about the axis of the goniometer.

For the feasibility test of the method we chose the rotor blades of a turbo vacuum pump (Type Leybold, TURBOVAC 150). The blades, made from aluminum, rotate at 50.000 rpm, so that centrifugal forces produce significant effects.

The experimental set up is shown in Fig. 2. When a rotor blade crosses the primary beam, the point of incidence of the beam upon the blade moves along the beam direction. Therefore, in a simple detection system with receiving slit in front of the counter, this movement would cause a line broadening, dependent on the - mostly unknown - angle of the blade surface with the beam. The centroid of the diffracted power would be given by the Bragg-angle and the centroid of the spatial distribution of the points of incidence. In parallel beam geometry, however, the line width is only determined by the convolution of the transmission function of the optical system with the line shape given by the properties of the sample like crystal structure, crystallite size, and strain. Above all the recording of the diffracted angle is unbiased by the momentary sample position.

In order to allow measurements at its nominal rotating frequency, the vacuum side of the pump was sealed by a capton window. Due to the construction of the pump, the accessible angular range was restricted to diffraction angles 2Θ above 120 degree. The upper limit of 140 degree was given by the diffractometer because the detector moved into the primary beam at higher angles. The monochromator had been set to a wavelength of 0.1436 nm. Only reflections (333) and (511) which coincide for cubic structures were accessible with this parameters. The tolerable displacement along the direction of the beam is given by

$$d = l \cdot \sin \Theta_A \; / \; (\; 2 \cdot \sin 2\Theta_S)$$

where l is the length of the analyser crystal and Θ_S and Θ_A are the Bragg angles

of the sample and the analyser respectively. With l = 70 mm, $\Theta_S = 67^0$, and $\Theta_A = 12.7^0$ we get d = 5.5 mm in each direction which is close to the radius of the entrance window of the detector.

The special construction of the diffractometer allowed easy replacement of the sample goniometer by the turbo pump. The pump was positioned in such a manner that the beam hit the roots of the rotor blades where the strains caused by the inertial forces due to the rotation are maximal. First we measured the reflection with the rotor at rest. Then we repeated the measurement with the rotor running with 50.000 rpm. The results of the two measurements are shown in Fig. 3. The reflection from the rotating blades is shifted towards higher angles relatively to the one from the blades at rest. This is a consequence of the contraction of the blades perpendicular to the elongation caused by the centrifugal force. Only this contraction is measured because the axis of rotation of the pump lies in the diffraction plane.

Comparision with theory

The contraction perpendicular to the acting force is given by

$$\mu_q = - \sigma \cdot \mu_l = - \sigma \cdot p \; / \; E$$

where σ is the Poisson ratio, μ_l the elongation in the direction of the force, E the Young modulus and p the force per unit area. The centrifugal force per unit area caused by the mass in the segment of a disk with a distance r from the center is given by

$$p = \rho \cdot (\; R^3 - r^3 \;) \cdot \omega^2 \; / \; (\; 3 \cdot r \;)$$

where R is the radius of the disk, ρ its density and $\omega = 2\pi\nu$ the angular velocity. With the experimental parameters R = 50 mm, r = 25 mm, ν = 833 Hz and the material constants of aluminum $\rho = 2.7$ g/cm^3, $E = 7 \cdot 10^{10}$ N/m^2 and $\sigma = 0.34$ we get $p = 10^8$ N/m^2 and finally

$$\mu_q = 0.5 \cdot 10^{-3}$$

This has to be compared with the change of the lattice constant which can be derived from Braggs law

$$\lambda = 2d \cdot \sin \theta$$

by differentiation

$$- \Delta d / d = \Delta\theta \cdot \cot \theta$$

with $\Delta\theta$ = 0.16 degree and θ = 67 degree we get $\Delta d/d = -1.2 \cdot 10^{-3}$ which deviates from the theoretical value by a factor of 2.4. This deviation can have several reasons. First, the blades do not have exactly the form of circle segments. Second, vibrations might cause additional strains. Third, the point where the beam hits the blades exactly could only be estimated during the feasability test of the method. Many other reasons for the observed deviation are possible. Nevertheless this experiment proved the feasability of strain measurements on moving objects and gave reasonable results.
The theoretical FWHM is given by the convolution integral of the optical elements. These components are the source which is polychromatic and has a small but non negligible divergence of about 0.14 mrad and the monochromator and analyser crystals where the reflection width is given by the dynamical theory of X-ray diffraction. From the calculation we got a FWHM of 0.16 degree for a diffraction angle $2\theta_S$ = 134 degree which is in excellent agreement with measurements we made using a sample of Germanium powder (4). The observed peak broadening (experimental FWHM about 0.5 degree for the rotating pump as well as for the pump at rest) can thus be attributed to sample properties like grain size effects and residual stress.

Future prospects

In this first experiment we used a beam of 3•3 mm^2 and registered the scattered photons during the whole rotation which means that we integrated over a ring including all blades. Position resolved measurements are also possible if the beamsize is reduced and the counter is gated by a signal having the frequency of

the motion. Due to the high intensity and collimation of the synchrotron radiation source even investigations of single crystal grains are possible.
Although the experimental resolution is already higher than the peak width given by this sample it is desirable to increase the resolution further. This can be achieved by minimizing the dispersion by a proper choice of the Bragg angles of monochromator, sample and analyser. Peak widths as narrow as 0.01 degree have already been measured in the nondispersive setting of this components.
Due to the small FWHM of the optical transmission function the measured line profile reflects the strain and grain size in the sample. So, a careful analysis of the changes in line shape at different rotation speeds may be helpful to detect density fluctuations caused by resonances in the material.
Another application of the method is the investigation of materials near their melting points, when mechanical instabilities cause deformations of the sample or its surface.

Conclusion

Our new method allows strain measurements of very high accuracy and is not affected by deviations of the sample geometry and position from the ideal one. The range within which the surface of the sample is allowed to deviate is only limited by the dimensions of the analyser and the detector window. Tolerances of several centimetres can be realized with standard components. Strain measurements are thus no longer limited by the accuracy of the sample alignment. This property was used for the determination of strain in a moving object. The first results show that this method is a powerful tool to enter into a new field of material research.

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SRI Conference 1987, Madison, Wisconsin
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Figure captions

Figure 1:
Path of the monochromatic beam in parallel beam geometry. In a) a set of parallel foils acts as collimator. In b) collimation is done by a single crystal which only reflects the rays into the detector which fall onto the crystal under the Bragg-angle. The dashed line shows the path of a beam reflected at a displaced sample, demonstrating that the same angle is measured as long as the beam fits into the analysing system.

Figure 2:
Beam path of the experiment. The accessible angular range was limited by the housing of the pump and the beam-tube of the primary beam.

Figure 3:
333,511-reflection from the rotor blades of the turbo pump. The solid curve showing the refection profile of the rotating pump (50000 rpm) is shifted to higher angles with respect to the reflection from the blades at rest (dashed).

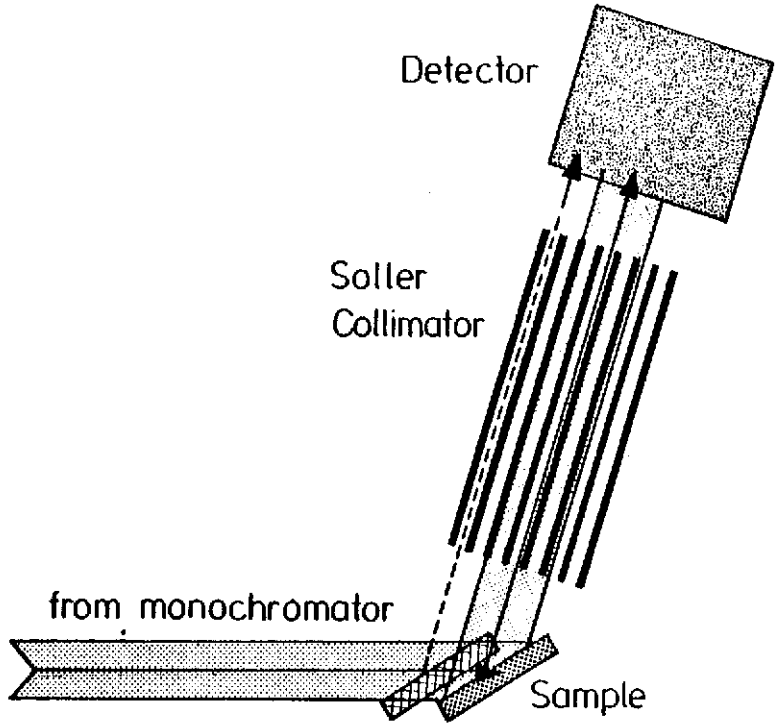

Fig. 1a

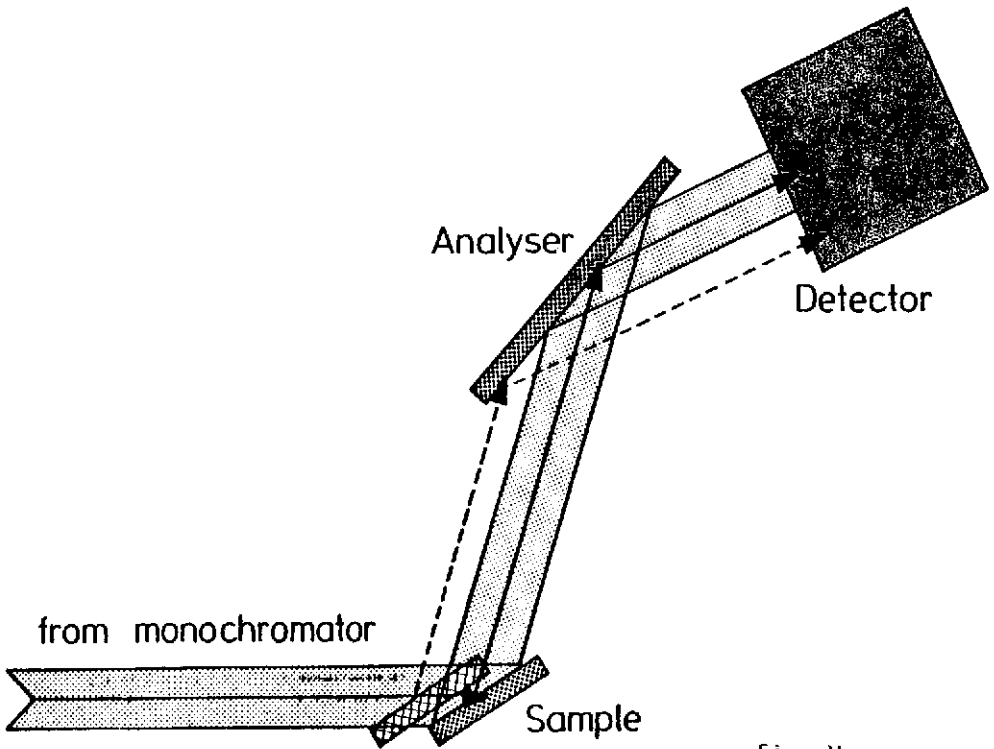
Analyser
Detector
from monochromator
Sample

Fig. 1b

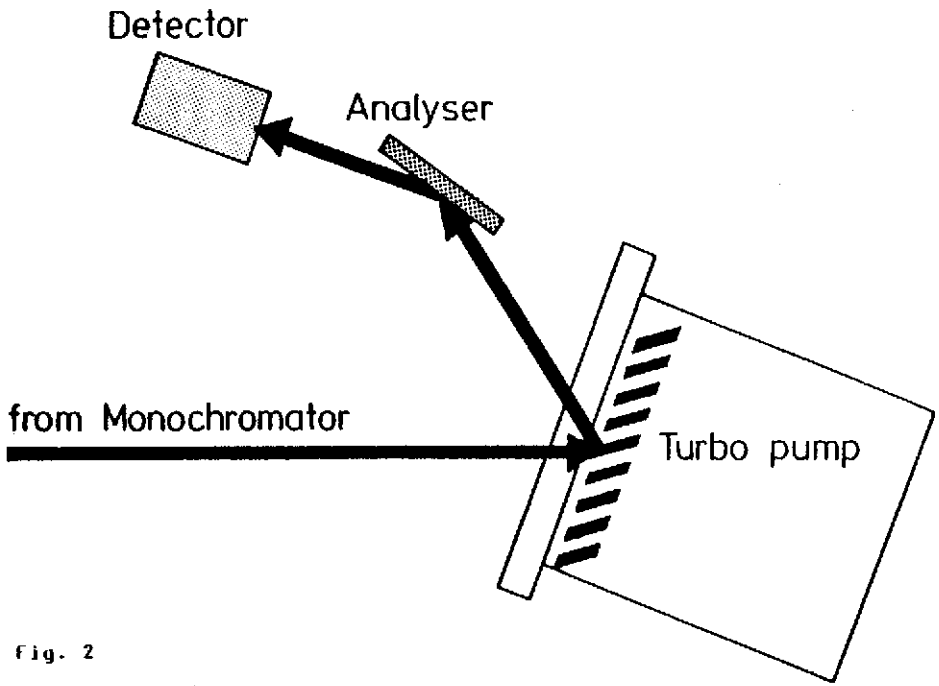
Detector
Analyser
from Monochromator
Turbo pump

Fig. 2

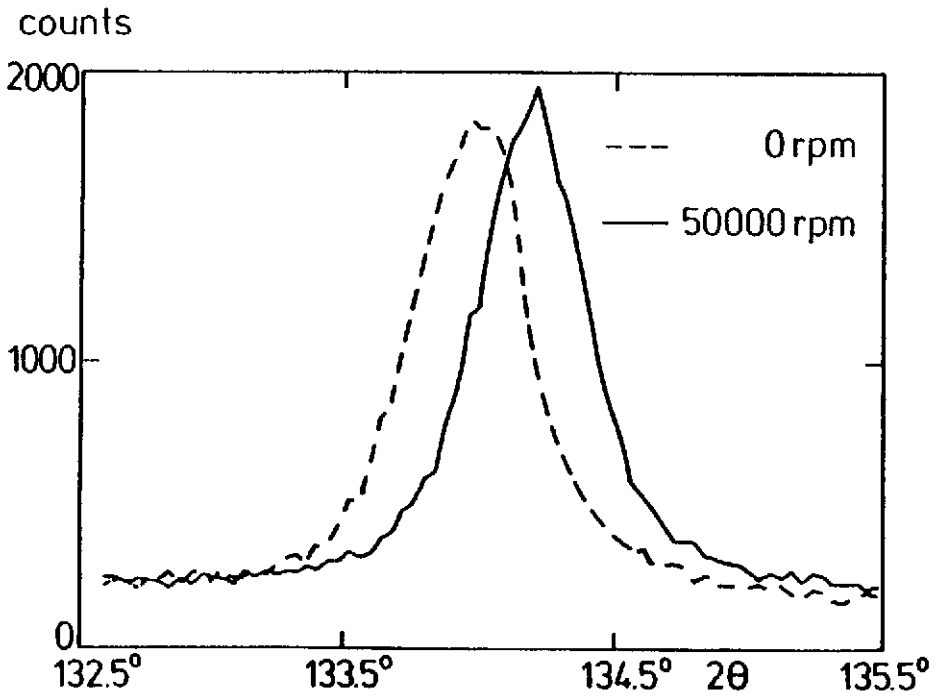

Fig. 3