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A New Approach to Fast and Automated Residual Stress Measurements

Introduction

X-ray diffraction is widely used as a non-destructive test method to determine residual stresses in polycrystalline materials. Apart from line detectors used for the well-established $\sin^2\psi$ method, two dimensional detectors such as imaging plates (IPs) and semiconductor detectors have been gradually introduced to X-ray stress analysers. The application of these detectors provides a new approach to fast and automated stress measurements with portable equipment.

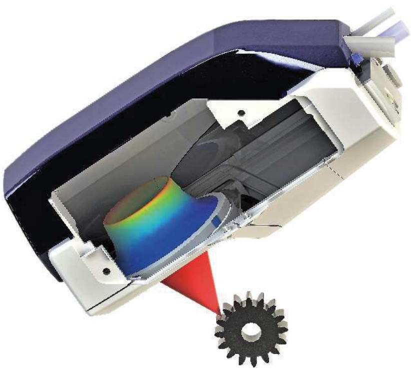

Figure 1: Principle picture of the sensor unit

Pulstec Industrial CO.,LTD. in Japan developed and released a portable X-ray residual stress analyser already in 2012, see Figure 1. The PULSTEC µ-X360 series is based on the cosα method for stress calculation. The method utilises the whole Debye-Scherrer ring, recorded on a two-dimensional detector and by a single incident angle X-ray exposure. The simple optical system of the µ-X360s reduces radiation energy remarkably, makes the stress analyser light, small, portable, very fast and thus more convenient to use for on-site and field measurements.
The latest µ-X360s can output a residual stress measurement result in just under one minute when measuring ferritic base material. More than 400 units of the µ-X360 series are used worldwide in universities, research institutes and industrial companies with a wide variety of trades, such as automotive, automotive parts, steel, aviation, heavy machinery, railway and infrastructure. For a closer look at the measurement principle of the cosα technology, you may refer to the chapter at the end of this article.

In-Field Applications

Professor Eckehard Müller from the University of Applied Sciences in Bochum, Germany was the first Pulstec µ-X360s user in Central Europe. After its delivery in December 2016, Müller´s unit has now been in permanent use over more than four years with more than 20,000 measurements and 270 tube hours performed without any problems. About 25% of these measurements took place outside the laboratory. The main reason was the dimension of the specimens.
Examples for such big parts are driving rods and shafts for railway engines, rollers for the steel industry, bearings, gears for wind power plants, and many others. All measurements could be performed in the normal industrial environment utilising a specific license for mobile measurements.
Figure 2 shows a measurement setup for a big roller bar. The X-ray stress analyser is easy to mount to a table or a trolley. The positioning of the measurement spot is easily done with the help of a laser pointing in the same position as the X-ray. The safety zone around the measurement spot is limited to only two meters.
Within this setup it is easily possible to perform an extended measurement program for 20 roller bars within one working day. This program usually includes stress determination along and perpendicular to the roller axis on a high number of spots, and even the internal transport.
Because of the low power consumption, the µ-X360s can be powered by a convenient battery pack. In combination with an optional flexible arm and a tripod where necessary, there are virtually no limitations to remote use cases. All of the equipment including an electro-polishing machine for stress profiles can be easily carried in customised transportation cases, so one of the upcoming interesting free field measurement tasks enabled by the advanced portability is to determine residual stresses on tram rails during non-operation times at night.
Professor Müller as with most other customers is pleased with the reliable results in extremely short measuring cycles. Müller and many other µ-X360s users removed their initial doubts on the comparability with the traditional $\sin^2\psi$ method by several investigations documented in a growing number of papers and theses. In the lab of the Bochum University of Applied Sciences for example, residual stress states in spring steel were analysed [1]. Other institutes have placed their focus on

Figure 2: In-field measurement on a roller bar utilising a flexible arm

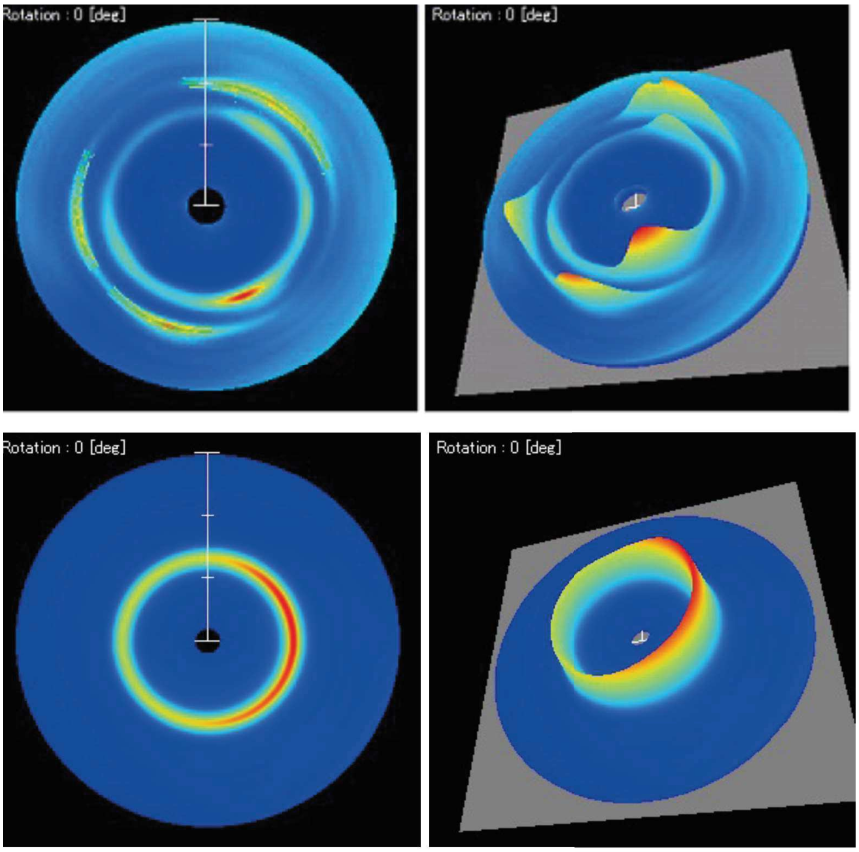

Figure 3: Debye-Scherrer rings taken from specimen with coarse grain (top) and texture (bottom)

different materials [2–4].

In addition to residual stress values, the user also gets valuable visible information from the Debye-Scherrer ring structure. Uneven signal intensity distribution over the ring circumference gives hints to coarse grain structure or texture as shown in Figure 3. With the μ-X360s software, it is also possible to calculate residual stresses from imperfect respectively incomplete Debye-Scherrer rings due to shading of the diffraction cone. How to calculate stress from such an imperfect ring is shown here [5].

Apart from laboratory use, the μ-X360s is on its way into industrial applications in production environments. First applications in serial parts production of springs, tools and gears are being prepared and implemented. In-line stress determination instead of delayed lab procedures allows for much faster production quality control and failure analysis. One major requirement for this development is the automation of measurement procedures, very often realised by the help of robots and suitable software solutions.

Automated Measurements with the μ-X360s

Utilising the fast measurements and easy setup of the μ-X360s, highly automated measurements on a huge variety of specimen are possible. Moreover, low radiation hazards and reduced safety restrictions allow for measurements in a production environment. Using a robot or a conveyor, belt parts can be placed automatically underneath the μ-X360s for measurements. Alternatively the robot or other handlinq equipment moves the μ-X360s sensor unit into position, as in Figure 4. This is easily possible due to the low requirements in accuracy of distance and angle between the detector and the specimen surface.

Using a robot and Sentenso's additional StressEasy control software further automation functions are available:

- Evaluation (OK / not OK) measurements
- Oscillation methods (linear, circular, ψ-angle)
- Out-of-plane shear stress determination

Figure 4: Measurement on a turbine disk with the help of a collaborative robot

- Stress tensor determination
- Repeated measurements
- Stress mappings

With the use of the StressEasy evaluation function parts can be measured in line and categorized into "OK" or "not OK", so problems in production line can be identified. With the help of a robot, even multiple measurements on one part are possible. If a measurement is out of range it is tagged in the software and a signal is given out to the PLC so the part can be routed accordingly.

Some specimens have a coarse grain structure or texture, which shows as uneven Debye-Scherrer ring on the detector. In case such a ring is not suitable for residual stress determination, there are several oscillation methods that help to improve the measurement signal. During a measurement, either the X-ray spot on the part is oscillated linearly or circularly to the original measurement spot, or the incident angle ψ is oscillated by a small degree keeping the position on the specimen. In this way, data from more independent grains is collected and improves on the spottiness of the Debye-Scherrer ring. The oscillation techniques are described in [6,7] as well.

Performing multiple measurements on the same spot from different φ angles StressEasy can calculate the out-of-plane shear stress components from just two measurements and the complete stress tensor from four measurements. The theoretical background can be found here [7].

Finally stress mapping is a very powerful feature. Imagine developing an induction heating process. One of the challenges in this development is predicting the residual stress distribution with certain parameters. With StressEasy software extension, you set up mappings of a whole specimen surface easily and automatically. Figure 5 shows such a mapping around an induction-heated spot with 21x21=441 measurements performed in just under seven hours. Mappings like these provide valuable information about the stress distribution on your part and enable targeted optimisation of production processes with only a short waiting time for measurement results. The results can also be used in simulations to further improve the processes.

Other very interesting applications for the mapping feature are gear tooth flanks, weldings and additive manufactured parts. Especially on AM parts, strong residual stresses can be found that cause unwanted deformation. By using the mapping function, production parameters can be optimised recursively and highly improve upon existing practices.

Basic Measurement Principle

The cosα method is based on Bragg diffraction by polycrystalline materials. The incident X-ray is diffracted at angles satisfying the equation

$$n\lambda=2d \sin \theta \qquad (1)$$

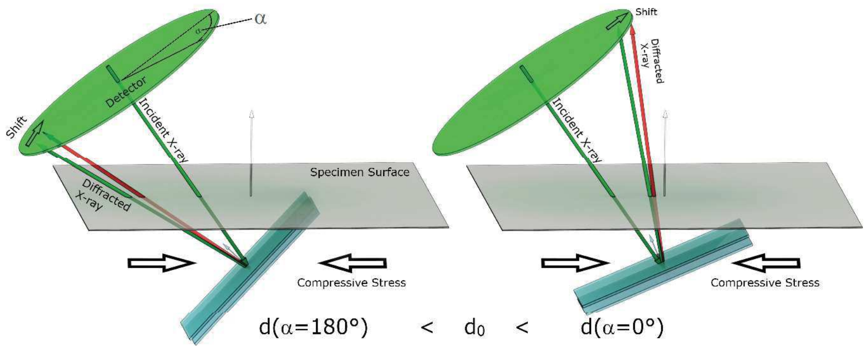

Figure 6: Basic measurement principle. Red arrow represents diffracted X-ray under compressive stress, green arrow under stress-free conditions

where θ is dependent on the lattice plane distance (d) and the discrete wavelength (λ) of the X-ray source [7]. For stress-free specimen, the lattice plane distance will be equal to d_0 for every lattice orientation relative to the surface. This creates a diffraction cone with a rotational symmetric axis collinear with the incident X-ray. The cone is projected onto the detector surface as a centric and round Debye-Scherrer ring. Introducing stress into the material will cause the lattice plane distance d to be different for different orientations relative to the specimen surface, as in Figure 6. For example near-parallel-oriented planes will widen and near vertical planes will compress under biaxial stress. The different lattice distances result in different diffraction angles (2θ).

The angle α on the detector plane represents the lattice plane orientation to the surface. The ring area around α = 0° shows diffraction peaks from near-parallel to surface lattice planes, where the area around 180° shows diffraction peaks from near-vertical to surface lattice planes. In general, different α angles represent different lattice plane distances d(α).
So, stress-related changes of the lattice distances lead to the diffraction cone being tilted in the measurement direction. On the detector the Debye-Scherrer ring is then shifted out of its original centre as per Figure 7, and may also be deformed. The residual stress is then calculated from the following equations:

$$\varepsilon_{\alpha 1} = \frac{1}{2}\{(\varepsilon_{\alpha} - \varepsilon_{\pi+\alpha}) + (\varepsilon_{-\alpha} - \varepsilon_{\pi-\alpha})\} \qquad (2)$$

$$\sigma_x = -\frac{E}{1+\nu}\cdot\frac{1}{\sin 2\eta}\cdot\frac{1}{\sin 2\psi_0}\cdot\left(\frac{\partial \varepsilon_{\alpha 1}}{\partial \cos \alpha}\right) \qquad (3)$$

To calculate stress from equation (3) the shift of the Debye-Scherrer ring over cos alpha (use symbol) is multiplied by material constants. This will give you a graph where the slope is proportional to the stress.

From the Debye-Scherrer ring it is also possible to calculate in-plane shear stresses in the case that the out of plane shear stresses are zero. out-of-plane shear stresses exist a second exposure with a different φ angle is needed to calculate the stress components. The determination of triaxial stress states is also possible but will not be discussed here. Please refer to [7] for further explanations.

Publication and Standardisation

Many academic papers on applications with the cosα method and the μ-X360s

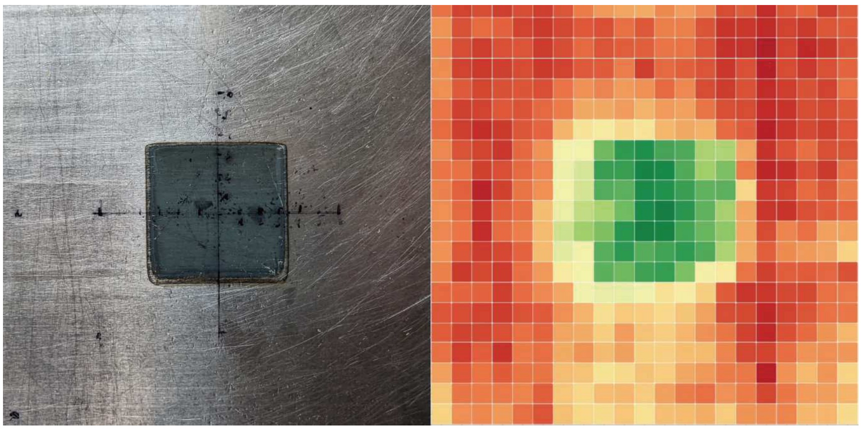

Figure 5: Stress mapping done on a ferritic steel component with an induction-hardened spot. Red corresponds to compressive and green to tensile stress

stress analyser have been presented and published globally, with some of these papers discussing the comparability of measurement results with the $\sin^2\psi$ method [1,2,4,8], while among other topics, it is also shown how the PULSTEC device with its small measurement head and the low radiation output can simplify in-situ measurements, for example in machine tools. [9].

Because of the growing number of installations and applications, the X-ray Material Strength Committee in The Society for Materials Science, JAPAN, published the Standard SMS SD 14 20, “Standard Method for X-Ray Stress Measurement by the $\cos\alpha$ Method” in February, 2020 [10]. This document is currently being translated into English. The organisation has already published a $\sin^2\psi$ edition in the past, and the items in $\cos\alpha$ edition follow the previous one including measurement condition, basic formula of stress, shear stress and principle of stress measurement. Other standardisation efforts have been made by the Japan Society for Non-destructive Inspection (JSNDI) [11].

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