

A New Type of X-ray Diffractometer with Cooperating Robots for Residual Stress Analysis on Large Components

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Abstract. For industrial applications concerning the nondestructive characterization of the near-surface material condition in terms of residual stresses, work hardening, phase transformation and formation of reaction compounds there is a strong demand for X-ray diffraction measurements on large components with complex geometry. Because many regions of interest on these components are not accessible with conventional laboratory or even mobile X-ray diffractometers, a novel center-free diffractometer with two cooperating robots named "Charon XRD" has been developed at MTU Aero Engines. Using a special optical measuring system to synchronize the two six-axis robots it was possible to achieve positioning accuracies that are comparable to those of conventional stationary diffractometers. This paper describes the design and functionality of Charon XRD and presents calibration and reference measurements, along with first measurements on aero-engine components.

1 Introduction

In industrial fields like aircraft engine construction, components must satisfy stringent requirements regarding reliability, weight, performance, cost-effectiveness and life. Therefore, it is crucial to achieve the full potential of the materials employed. From this aspect, component surfaces and sub-surface layers are of special interest, considering that they normally show maximum operating loads and therefore are most likely the source of potential failures.

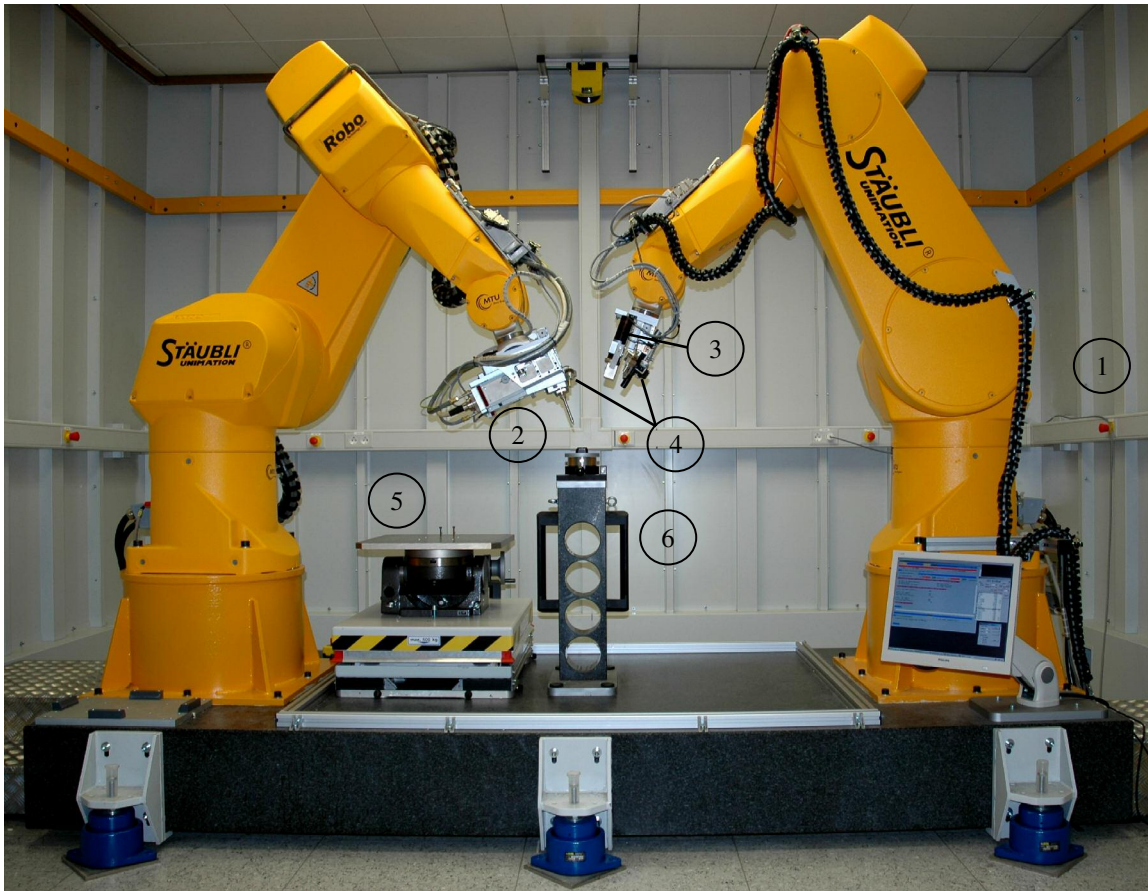
For the nondestructive characterization of near-surface residual stresses and work hardening on various large complex-geometry components that are inaccessible to mobile diffractometers, MTU Aero Engines developed its first stationary large X-ray diffractometer 13 years ago [1]. The results obtained with this freely positionable laboratory diffractometer system were used predominantly for optimisation and monitoring manufacturing processes, resolve manufacturing deviations, for damage analyses and assessment of new production technologies.

To use the results also in life analysis, nondestructive inspection of the material conditions in the near-surface zone over the life of the component will become necessary (s. e.g. [2-4]). Against this background, and because of new production technologies being developed, constantly increasing measuring tasks on large complex components used in engine construction are required, such as in blisk (= bladed disks) technology for aircraft engines. Accordingly, the existing diffractometer at MTU Aero Engines needed replacing with a newly developed, robust, more powerful and production-capable large X-ray diffractometer for surface stress analyses.

The new "Charon XRD" diffractometer was implemented in accordance with MTU's concept in partnership with GE Inspection Technologies, and Robo-Technology [5]. The novel diffractometer concept uses two cooperating six-axis robots that position the X-ray tube and the detector in diffraction geometry relative to the component surface. Apart from achieving considerable flexibility re-

garding the component geometries to be measured, the aim also was to obtain high positioning and measuring accuracies, fast analysis rates, high maintainability, and user friendliness.

2 Design, function and measuring options



GE
Inspection Technologies

Charon XRD

concept by
MTU Aero Engines

robot control by
Robo-Technology



Fig. 1: Interior view of the Charon XRD X-ray robot diffractometer. 1 = radiation protection cabin, 2 = X-ray source, 3 = X-ray detector, 4 = optical measuring system, 5 = component positioning unit, 6 = audit column.

The Charon XRD system illustrated in Fig. 1 includes three main subsystems:

Radiation protection cabin. The robot diffractometer is surrounded by a walk-in X-ray protection cabin providing maximum safety standards. Wide doors allow easy access for comfortable loading of large components. During operation the cabin interior can be monitored through windows in the door and with a controllable camera from the control console. To preclude mechanical collisions from uncontrolled robot movements the cabin walls are protected by wide area motion sensitive scanners. The cabin temperature is held constant within $\pm 1^\circ\text{C}$.

Robot diffractometer and component positioning unit. The X-ray tube and the detector are each guided by a six-axis RX170B-HP industrial robot from Stäubli. This robot type has a range of 1835 mm and a maximum load capacity of 60 kg with the best presently available spatial positioning accuracy. Each robot moves, referred to its own coordinate system, with an absolute positioning accuracy of ± 0.5 mm when approaching a point and an angular accuracy of $\pm 0.03^\circ$. At constant temperature, its repeatability is about ± 0.04 mm.

The two robots are fixed on an elastically supported 3250 x 1350 x 300 mm³ granite slab to protect against external vibrations. The robots were arranged on the slab in a manner such that between them, they can accommodate components sized at least 700 x 700 x 500 mm³ and the optimally measurable volume of 300 x 300 x 300 mm³ is also located midway between the two robots, 850 mm above the slab.

In order to make stress measurements with diffraction angles 2θ up to 170° , the X-ray source housing and scintillation detector are each mounted with a corresponding aperture slit system on respective robots in a very compact design. This allowed attachment of optical measuring devices to each side without unnecessary reduction of any beam paths.

The optical measuring system is an essential part of the new diffractometer and is specially developed (patent pending) to synchronize the two robots. This compact measuring system was optimized so that the angle between the incident and diffracted X-ray beam could permanently be determined within $\pm 0.001^\circ$, and the linear positioning within ± 0.01 mm relative to the component surface in the direction of the bisector of this intermediate angle, in the common coordinate system. Fig. 2 shows details of the optical measuring system.

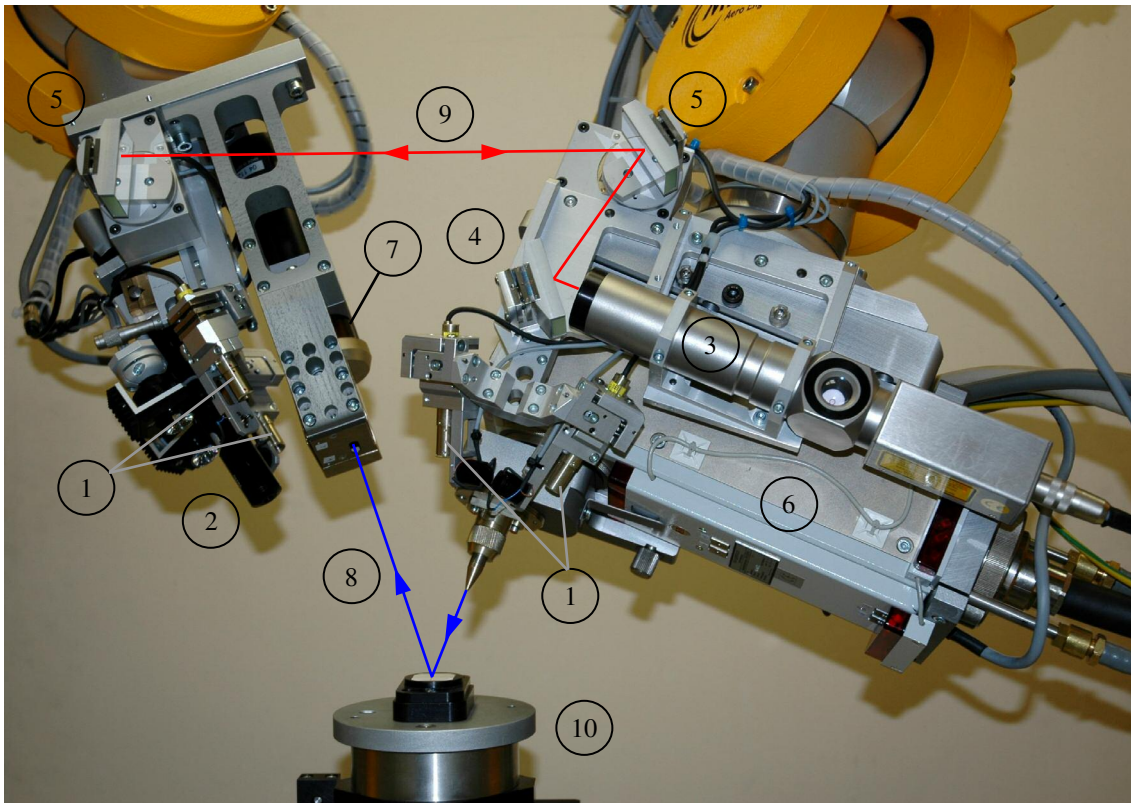


Fig. 2: Detailed view of the optical measuring system to synchronize the two robots. 1= laser line projectors, 2 = camera system, 3 = autocollimation telescope, 4 = fixed deflector mirror, 5 = movable deflector mirror, 6 = X-ray source, 7 = X-ray detector, 8 = X-ray beam, 9 = laser beam, 10 = audit column.

To control the desired position of the incident and diffracted X-ray beam relative to the component surface, two laser line projectors are mounted on each robot near the X-ray source and the detector. The laser line projectors on each robot are adjusted to each other in such a way, that the generated light planes intersect and the sectional line coincides with the X-ray beam direction during diffraction measurements. Accordingly, the intersection of the laser lines on a plane intersecting the light planes marks the position of the X-ray beam.

By means of LED illumination and a small industrial CCD camera with a large depth of field, the projected crossed lines from the tube and detector robots and the marked measurement target

point on the component (e.g., a color cross or the light spot of an optical waveguide) are captured and automatically evaluated for a fast iterative position refinement of the two robots until all markers intersect at one point. At a measuring distance of 200 mm, the camera resolution is about 5 μm and the viewing area is about 5 x 5 mm².

The intermediate angle of the X-ray beams is controlled by a laser-based autocollimation telescope, in combination with deflector mirrors mounted on high-precision rotary stages for automatically angle dependent adjustment.

Another part of the equipment is an angularly adjustable lift table with air cushion guidance that allows components up to 400 kg in weight to be readily positioned in the diffractometer.

Control and X-ray evaluation software. Standard software is used to control the diffractometer and to evaluate and document measurement results. During operation of the Charon XRD, strict separation is made in the software between the actual diffractometer movements and the transport or alignment movements of the diffractometer proper.

The actual diffractometer movements in step scan mode are comparable with those of a θ - θ diffractometer [6] in either focussing Bragg-Brentano or parallel beam arrangement [7]. The measuring circle radii are independently variable between 150 und 450 mm (although for the Bragg-Brentano setup they must be the same size). Determination of the lattice strains can be made at a random azimuth angle ϕ of at least 90° in the χ - or ω -mode with a tilt angle range of $-70^\circ \leq \psi \leq +70^\circ$ (χ -mode) and $-45^\circ \leq \psi \leq +45^\circ$ (ω -mode) respectively. Residual stresses are determined using the well-known $\sin^2\psi$ method [8].

For surfaces of components inclined up to about $\pm 30^\circ$ relative to the horizontal, the diffractometer can be tilted automatically after a surface normal first has been optically determined. For optimized stress analysis for non-ideal material structures such as coarse-grained materials, special techniques like oscillations at azimuth and/or tilt angle movements, along with accumulations of measurements at various component positions, are possible. In the presence of strongly curved component surfaces, so-called angle-dependent absolute value corrections can be made. Component surfaces also can be automatically mapped by various techniques.

3 Calibration and reference measurements

To demonstrate the performance and accuracies achieved with the Charon XRD system, various calibration and reference samples were first measured with a high-precision XRD 3003 PTS laboratory system at GE Inspection Technologies in Ahrensburg. Afterwards these samples were measured again on the Charon XRD system at MTU Aero Engines in Munich, using comparable measuring geometries and measuring parameters as far as possible. The measurements were made with characteristic Cu $K\alpha$ and Cr $K\alpha$ radiation.

From the measurements on Si powder (SRM 640c) as a standard for calibration of diffraction line positions and line shapes, it was shown that the Charon XRD reproduces the certified reflection positions of the standard over the entire high 2θ angular range between 90° and 140° with an error of $\leq 0.01^\circ$ in 2θ .

General verification of the accuracy in the volume of 300 x 300 x 300 mm³ that can be measured without translation of the sample was made by X-ray diffraction measurements on a single-crystal silicon disk. Owing to its perfect crystal growth, this disk is homogenous and therefore theoretically provides identical peak positions with identical profiles everywhere on the surface. More particularly, positioning errors in measuring distance, 2θ angle, or orientation relative to the surface normal must result in relative deviations between the measured peak positions. For this purpose, the disk was tilted in x- and y-directions (about 30 degrees) and positioned in the center of the measurement volume (Fig. 3, left). The measured reflections show very good agreement at all measuring positions in the volume, i.e. peak position, intensity, full width at half maximum (FWHM) and resolution are identical within the measurement statistics (Fig. 3, mid and right).

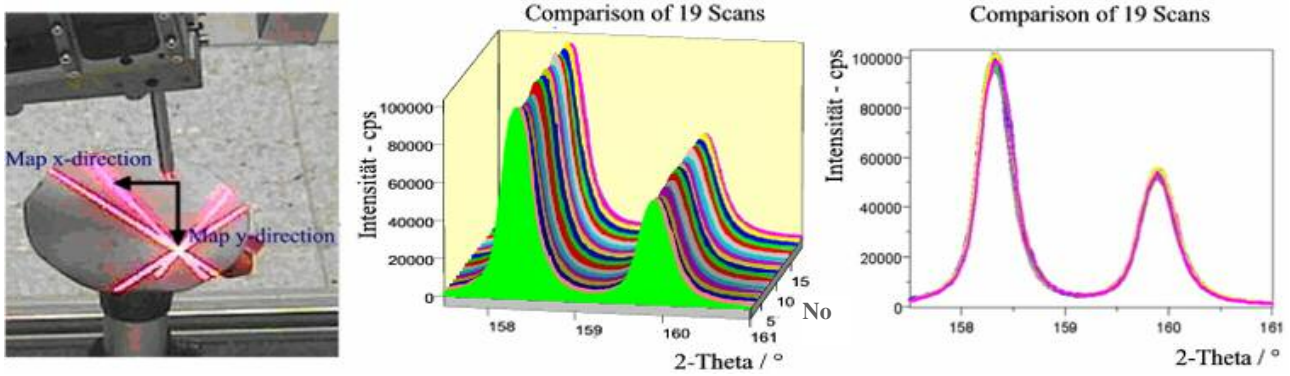


Fig. 3: Setup (left) and intensity profiles in 3D (mid) and 2D (right) of scans in x- and y-directions on tilted single-crystal silicon disk.

The properties and accuracies of the two diffractometer systems regarding the measurement of near-surface residual stresses were verified using residual stress-free Au and Fe reference powders [6]. A typical Charon XRD measurement result from standard Au powder on Charon XRD in χ -mode with tilt angle range from -70° to $+70^\circ$ is shown in Fig. 4.

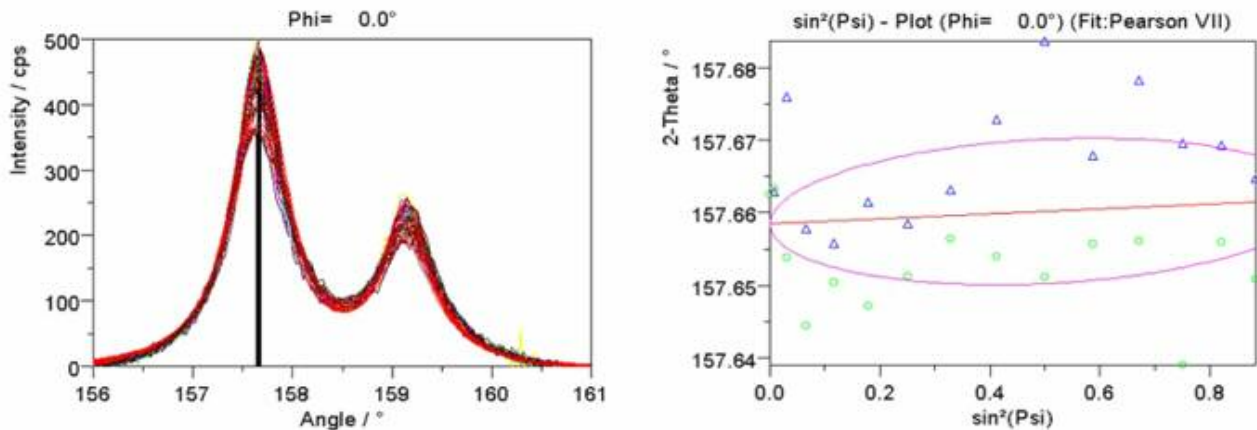


Fig. 4: Residual stress measurement on Au powder with tilt range from -70° to $+70^\circ$: Received peak positions (left) and peak positions vs. $\sin^2\psi$ diagram (right).

The maximum displacement $\Delta 2\theta$ of the calibration peaks do not exceed $\pm 0.02^\circ$ in 2θ throughout the total tilt angle range. A potential difference relative to the theoretical 2θ values of the powders can be used for absolute line position correction.

The investigation of stressed reference samples was made on ground and shot peened surface conditions of IN718 and Ti64, both typical aerospace materials. These samples have been measured on various diffractometers and their stress values have accordingly been validated continuously over a period of years. The given measurement data were confirmed within allowable error tolerance [9] through comparative series of measurements on the GE Inspection Technologies laboratory system and the Charon XRD.

4 Component measurements

To demonstrate the flexibility of Charon XRD, measurements on complex-geometry engine components at positions of interest inaccessible by conventional diffractometers is described below.

For example, nondestructively residual stress measurements in radial direction at various airfoil positions are necessary to optimize milling operations in blade manufacturing on a compressor blisk of a titanium base alloy. The test setup and a typical result from investigations are shown in Fig. 5. Lattice strain analyses were performed with Cu $K\alpha$ radiation on $\{213\}$ -lattice planes at 2θ of 140° in the respective maximally achievable tilt angle range.

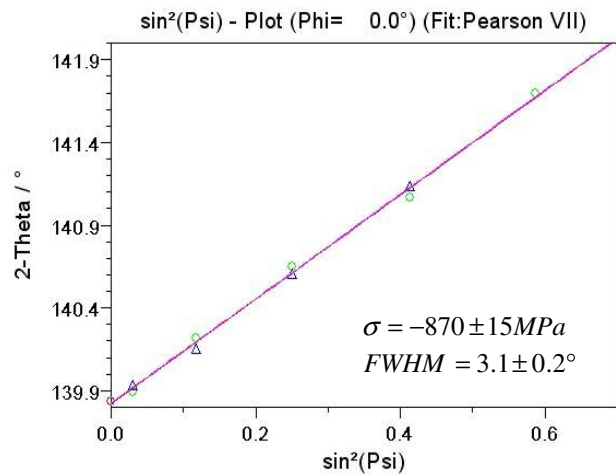
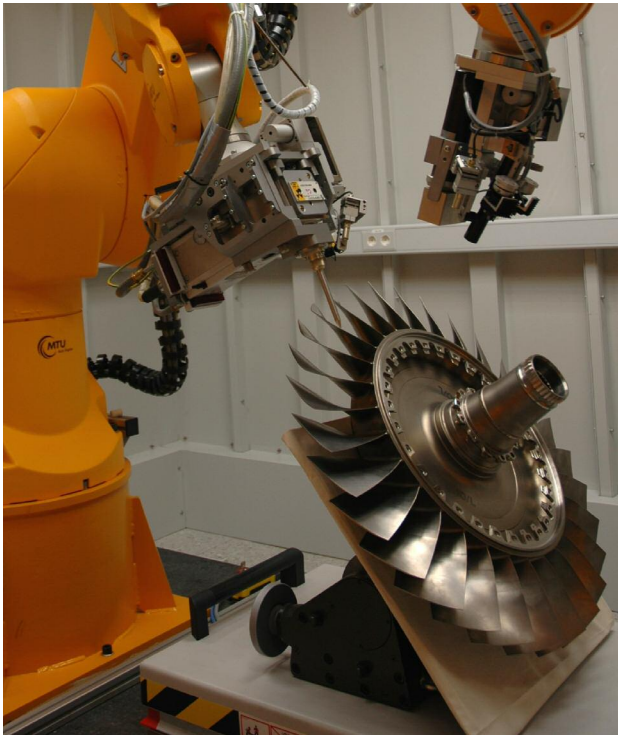


Fig. 5: Residual stress measurement on a compressor blisk (left) and a typical 2θ - $\sin^2\psi$ diagram with the determined results (right) at a measuring position near the blade edge in the blade root region.

5 Summary

Charon XRD is a center-free large X-ray diffractometer for stress analysis using a novel concept with two cooperating high-precision six-axis robots. The X-ray tube and the detector are each guided by one of the robots. Sufficient positioning accuracy of the two robots relative to one another in a common coordinate system, as required for diffractometer operation, is achieved through a newly developed permanently active optical measuring system providing an absolute angular accuracy of $\pm 0.001^\circ$ and linear positioning in one direction of ± 0.01 mm.

The Charon XRD system offers the following advantages over current conventional facilities:

- Maximum of flexibility in terms of component geometry, size and variety
- High measuring accuracy in the analysis of residual stress value
- Short analysis times, high maintainability and user-friendliness.

References

- [1] H.U. Baron, E. Bayer, L. Steinhauser, H. Bradaczek and E. Wasiewicz: *Europ. J. NDT* Vol. 3 No. 1 (1993), p. 17.
- [2] D. Greving, M. Gorelik and H. Kington: *Review of Progress in QNDE*, Vol. 24B, eds. D.O. Thompson and D.E. Chimenti, Plenum, New York, 2005, p. 1339.
- [3] S. Vulkelich, S. Berkley, S. Russ and E.F. Bradley: *Mat. Evaluation* (2002), p. 884.
- [4] R. John, J.M. Larson, D.J. Buchanan and N.E. Ashbaugh: *Proc. of the eighth Int. Fatigue Congress*, Vol. 2/5, Stockholm, Sweden, 2002, p. 1063.
- [5] MTU Aero Engines Report, winter 2005/spring 2006, p.10.
- [6] B. Scholtes, *Verfahrensbeschreibung, Röntgenographische Ermittlung von Spannungen* (AWT, 2000). DRAFT prEN 15305: *Non-destructive Testing - Test Method for Residual Stress analysis by X-ray Diffraction*, July 2005.
- [7] I.C. Noyan and J.B. Cohen: *Residual Stress - Measurement by Diffraction and Interpretation* (Springer, New York 1987).
- [8] E. Macherauch and P. Müller: *Z. angew. Physik* 13 (1961), p. 305.
- [9] V. Hauk: *Structural and Residual Stress Analysis by Nondestructive Methods* (Elsevier, Amsterdam, 1997).

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