# Charon XRD
# A New Twin Robot X-ray Diffractometer for Surface Analysis of Complex Aircraft Components

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**Abstract.** For the non-destructive characterization of near-surface material states concerning residual stresses and work hardening on large components with complex geometries, a novel center-free large X-ray diffractometer named "Charon XRD" was developed at MTU in a joint partnership project. GE Inspection Technologies with its fundamental knowledge in X-ray analysis combined successfully the proven concept of MTU Aero Engines and robot control solutions of ROBO Technology.
Using a special optical measuring device the positioning accuracies of currently available six-axis robots could be brought to the necessary precision and, for the first time, highly accurate control of two synchronized robots in one coordinate system became possible. Measurements allow to design new components using the full potential of the materials and to meet the requirements of quality control regarding reliability, weight, performance, cost-effectiveness and life. This paper describes the design, functionality and measuring options of Charon XRD. First measurements on aircraft components with complex geometries are presented.

## 1. Introduction

Among the conventional NDT methods X-ray diffraction has become more importance during the last years [1]. These predicted potentials were realized in the meantime as much as possible. MTU Aero Engines developed its first stationary large X-ray diffractometer 13 years ago with standard translation and rotary axes [2].

New production technologies being developed, required constantly increasing measuring tasks on large complex components used in engine construction, such as in blisk (= bladed disks) technology for aircraft engines. Component surfaces and subsurface layers are of special interest, considering that they normally show maximum operating loads and therefore are most likely the source of potential failures. Non-destructive characterization of near-surface residual stresses and work hardening on various large complex-geometry components are important to optimise and monitor manufacturing processes and eliminate manufacturing deviations.

Accordingly, the existing diffractometer at MTU Aero Engines needed replacing with a newly developed, robust, more powerful and production-capable large X-ray diffractometer "Charon XRD" for surface stress analyses. It was implemented in accordance with MTU's concept in partnership with GE Inspection Technologies, and Robo-Technology [3, 4, 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 regarding the component geometries to be measured, the aim also was to obtain high positioning and measuring accuracies, fast analysis rates, high endurance, easy maintainability, and user friendliness.

## 2. Design and Mode of Operation

The Charon XRD arrangement with two commercially available high-precision robots, illustrated in Fig. 1 and Fig. 2, includes three main subsystems:


Fig. 1: Outside view of the Charon XRD X-ray robot diffractometer.

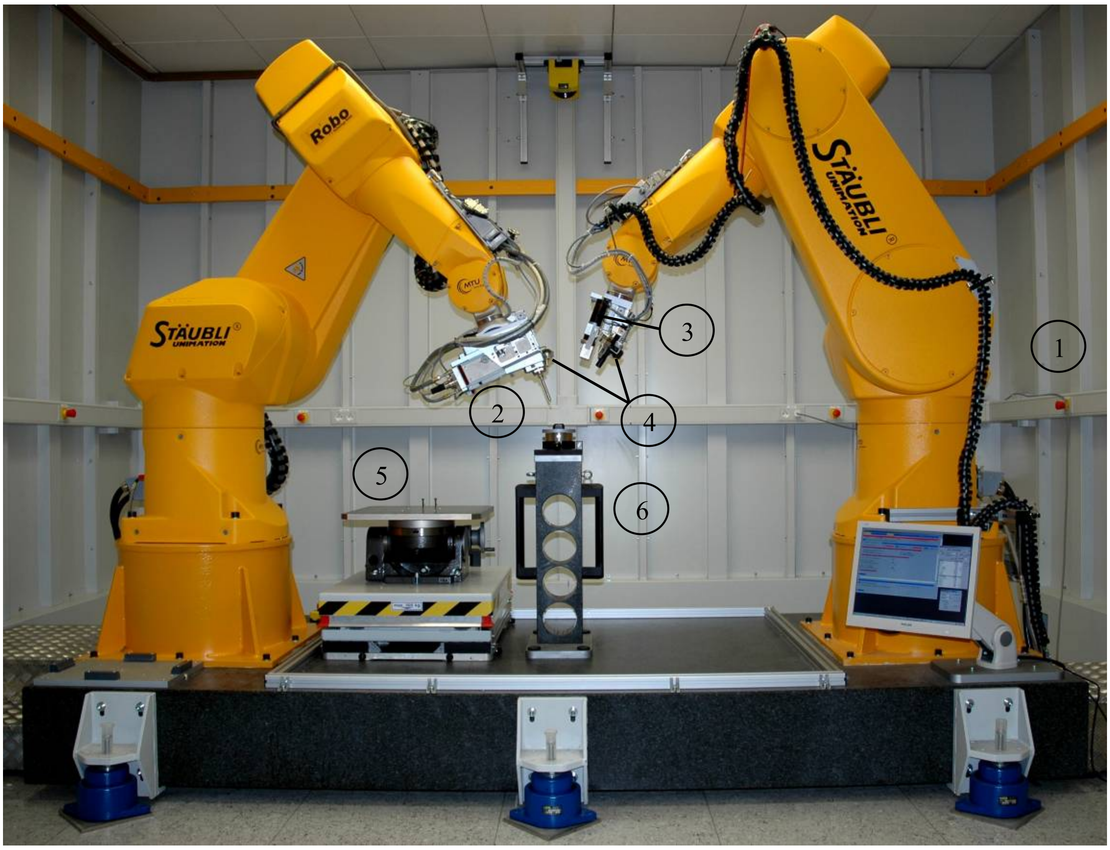



Fig. 2: Interior view of the Charon XRD X-ray robot diffractometer. 1 = radiation protection cabin, 2 = X-ray source, 3 = X-ray detector, 4 = optical measuring system, 5 = component positioning unit, 6 = audit column.

### *2.1 Robot X-ray Diffractometer System*

Two robots are fixed on an elastically supported 3250 x 1350 x 300 mm³ granite slab to protect against external vibrations. They are mounted in such a distance that between them components sized at least 700 x 700 x 500 mm³ are measurable in a volume of 300 x 300 x 300 mm³. An angularly adjustable lift table with air cushion guidance allows positioning of components up to 400 kg in weight.

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 ±0.03°. At constant temperature, its repeatability is about ±0.04 mm. To improve the precision the bearing play of the robot axes was eliminated by always approaching the desired position from one direction. For technical safety reasons, the robot travel rate was limited to 250 mm/s.

An essential part of the new diffractometer Charon XRD is a specially developed (patent pending) optical measuring system. This allows to determine the angle between the incident and diffracted X-ray beam permanently within ±0.001°, and the translations within ±0.01 mm relative to the component surface in the direction of the bisector of this intermediate angle. Fig. 3 shows details of the optical measuring system.

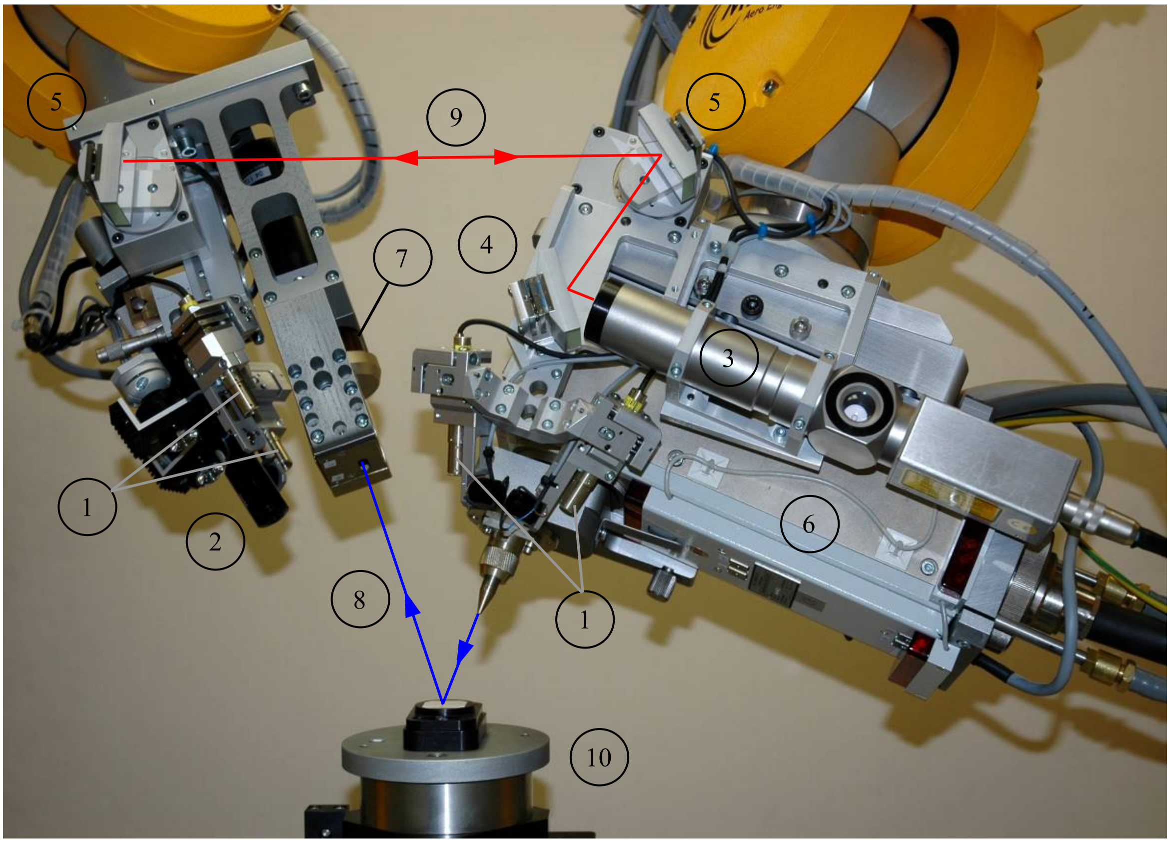



Fig. 3: Detailed view of the optical measuring system to synchronize the two robots. 1= laser line projectors, 2 = camera system, 3 = autocollimation telescope, 4 = fixed deflector mirror, 5 = movable deflector mirror, 6 = X-ray source, 7 = X-ray detector, 8 = X-ray beam, 9 = laser beam, 10 = audit column.

By means of a small CCD camera the projected crossed lines from two laser line projectors mounted on each robot near the X-ray source and the detector 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. This applies at least to the nominally usable range of the measuring circle radii from 200 to 450 mm.

The intermediate angle of 10 to 90° ($90° \leq 2\theta \leq 170°$) 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.

## *2.2 Control and X-ray Evaluation Software*

Standard SEIFERT RAYFLEX software is used to control the diffractometer and to evaluate and document measurement results.

The actual diffractometer movements, schematically shown in Fig. 4, are in step scan mode comparable with those of a θ-θ diffractometer [6] in either focussing Bragg-Brentano or parallel beam arrangement [7].

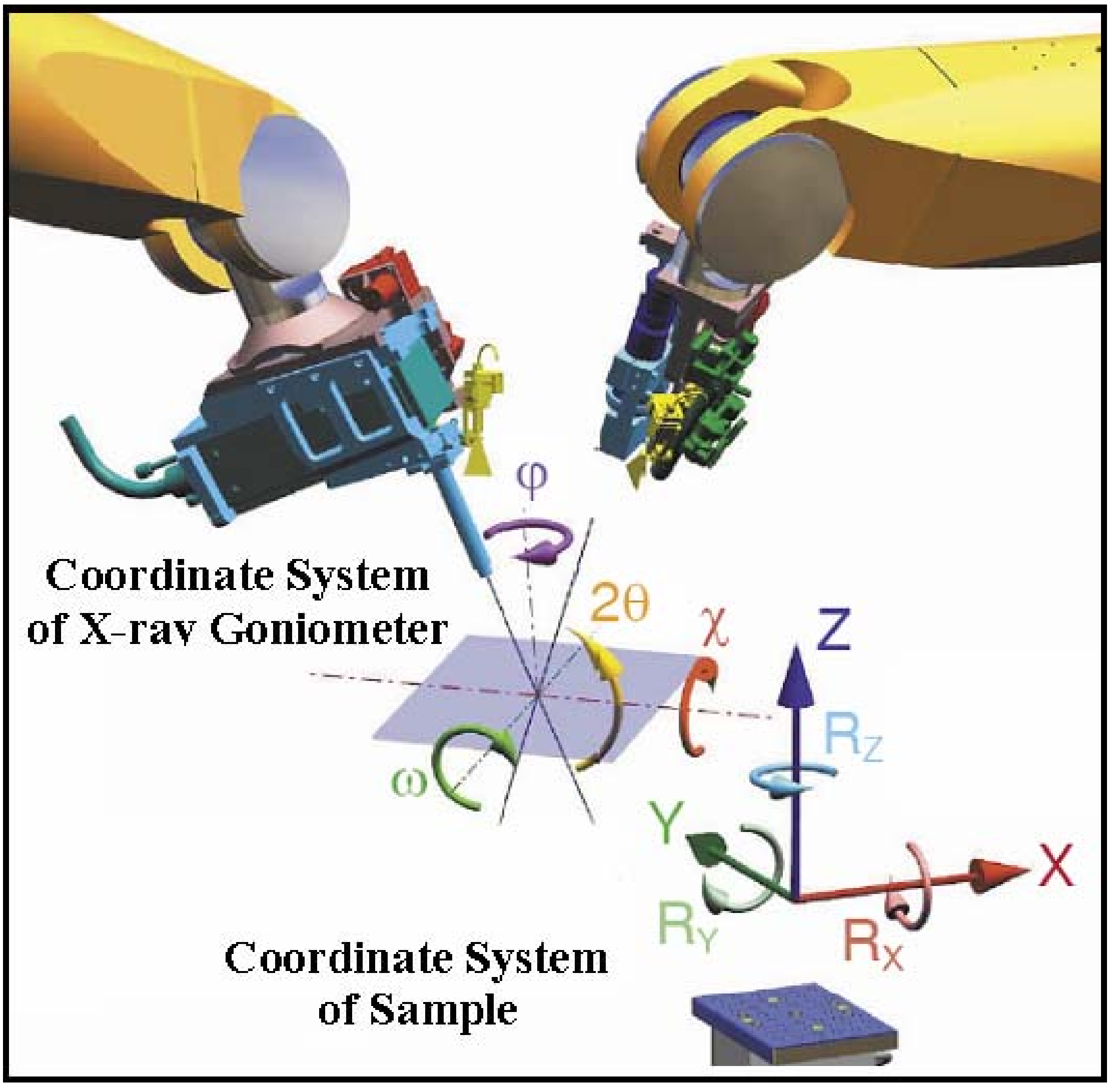



Fig. 4: Schematically view of X-ray goniometer and sample coordinate systems.

The measuring circle radii are independently variable between 200 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-mode [8] with a tilt angle range of $-70° \leq \psi \leq +70°$ or ω-mode with $-45° \leq \psi \leq +45°$ respectively. Residual stresses are determined using the $\sin^2\psi$ method [9].

For surfaces of components inclined up to about ±30° relative to the horizontal, the diffractometer can be tilted automatically after a surface normal has been optically determined first. Optimized stress analysis on non-ideal material structures such as coarse-grained materials are possible with special techniques like oscillations at azimuth and/or tilt angle movements, along with accumulations of measurements at various component positions. 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.

### *2.3 Radiation Protection Cabin*

Charon XRD 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 measuring heads of the tube and detector robot are completely surrounded with so-called software boxes to prevent collisions. The cabin temperature is held constant within ±1°C.

## 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 Kα and Cr Kα 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 with copper radiation the certified reflection positions over the certified 2θ angular range between 90° and 140° with an error of ≤ 0.01° 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 and 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, see Fig. 5, left.

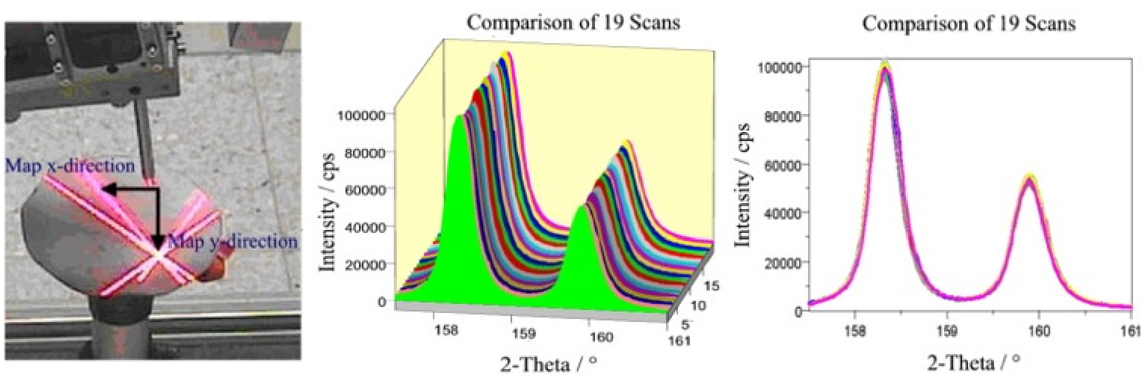



Fig. 5: Setup (left) and intensity profiles in 3D (mid) and 2D (right) of scans in x- and y-directions on tilted single-crystal silicon disk.

The measured reflections with Cu Kα radiation show very good agreement at all measuring positions in the volume, i.e. peak position, intensity, full width at half maximum and resolution are identical within the measurement statistics, see in Fig. 5, mid and right.

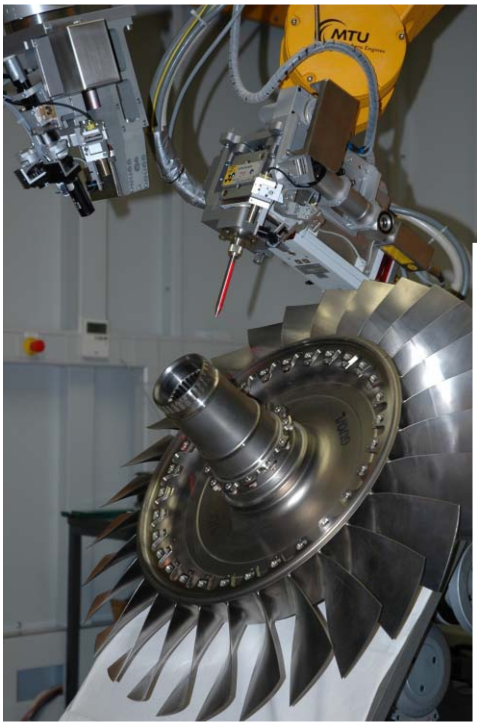
The properties and accuracies of the two diffractometer systems regarding the measurement of near-surface residual stresses were verified using residual stress-free Au and Fe reference powders [10].

For reproducibility tests both robots were intentionally positioned with high acceleration and extremely wide elongations for several times between two measurements on Au powder. The very good agreement of both curves shows a high stability also after extreme endurance testing. Reproducible adjustment between X-ray focus and collimator system with robust fixation allows easy changing of different X-ray tubes in less than 15 minutes . 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 results were confirmed within allowable error tolerance [11].

## 4. Measurements on Complex Aircraft Components

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, non-destructive 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 setups and a typical result from investigations are shown in Fig. 6. Lattice strain analyses were performed with Cu Kα radiation on {213}-lattice planes at 2θ of 140° in the respective achievable tilt angle range.



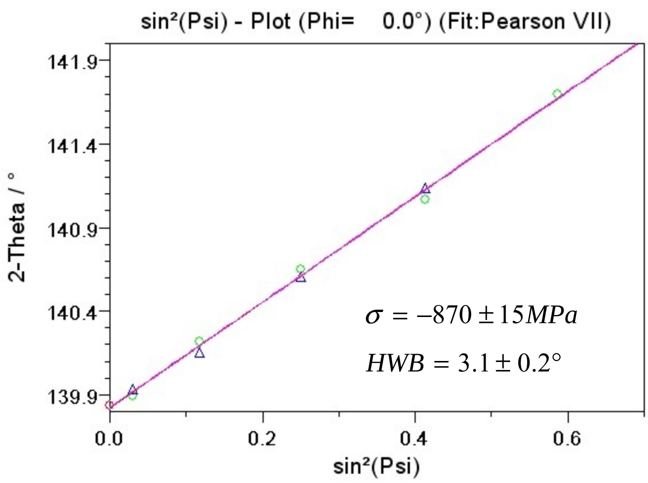




Fig. 6: Residual stress measurements on a compressor blisk in the Charon XRD diffractometer (left) and a typical 2θ-sin²ψ diagram with the determined results (right) at a measuring position near the blade edge in the blade root region.

For validation of a cast stator of a compressor in nickel base alloy non-destructive surface residual stress measurements in radial direction at various circumferential positions at different positions on the vibro polished airfoil surfaces near the blade edge and near the outer and inner shrouds were required. Fig. 7 shows the measuring setup and a typical result. Lattice strain analyses were performed with Mn Kα radiation on {311}-lattice planes at 2θ of 151°. Owing to the complex component geometry and the measuring position to be investigated, only a very limited range of tilt angle ψ could be used.

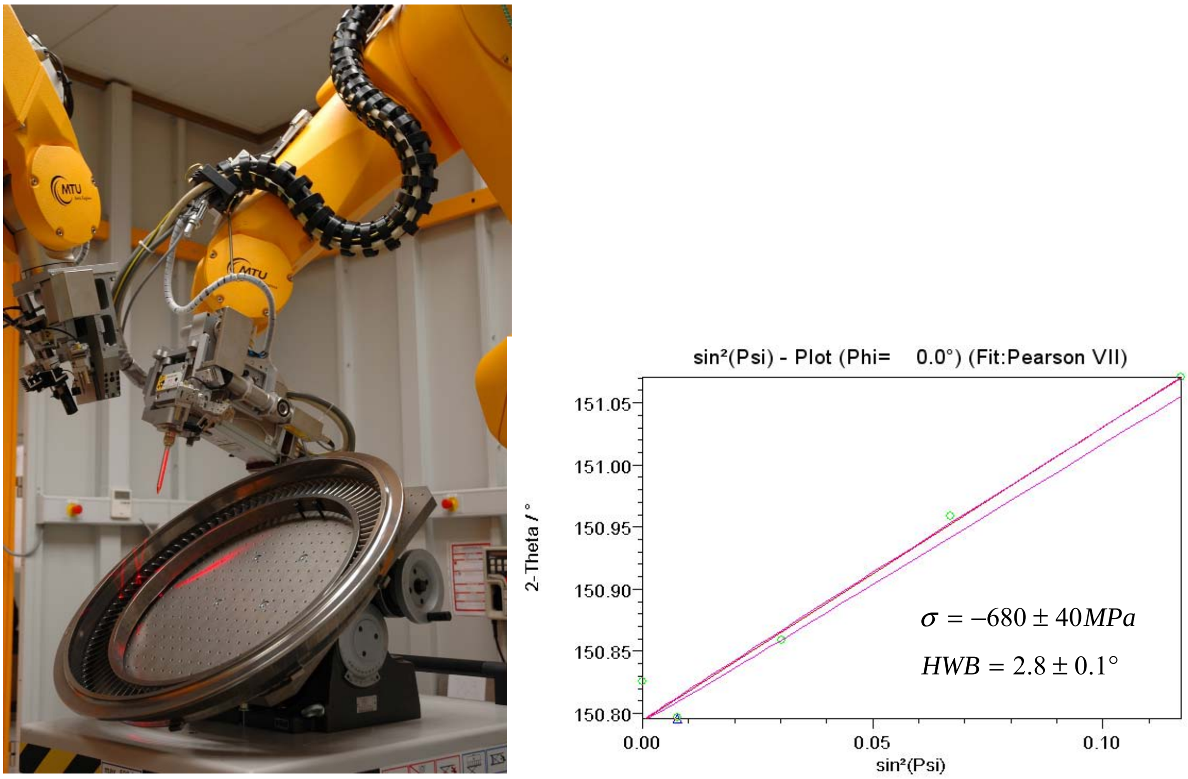



Fig. 7: Residual stress measurements on a stator of a compressor in the Charon XRD diffractometer (left) and a typical 2θ-sin²ψ diagram with the determined results (right) at a measuring position near the airfoil edge.

## 5. Outlook

Additional future potentials for faster measurements and higher throughput can be introduced by X-ray optics to increase intensity and by suitable Position Sensitive Detectors (PSD) for wide angular acceptance and highest sensitivity.

With first measurements on the lab system XRD 3003 PTS it was shown that minilens-optics generate a 6 times higher X-ray spot intensity on the specimen.

The curves in Fig. 8 show a typical example of peak intensities obtained during X-ray measurements on 100 Cr 6 reference sample B524 [12] with compressive stresses introduced by grinding. An additional time reduction by factor 10 is available by using a PSD detector.

Minilens for primary optic combined with PSD allows 60 times faster measurements.

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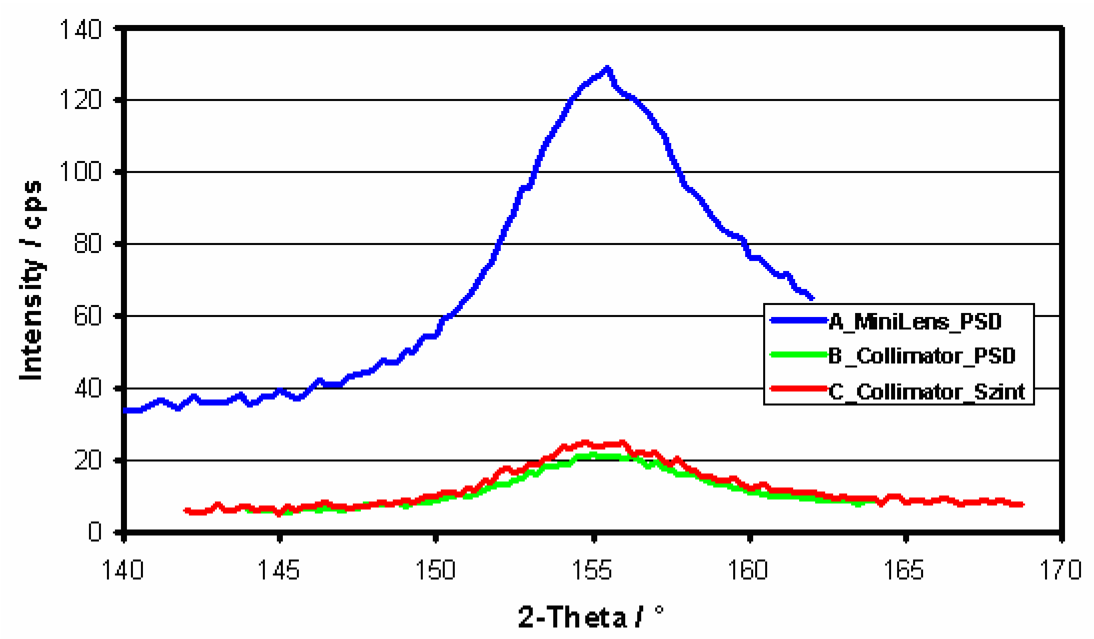


Fig. 8: X-ray diffraction measurements on 100 Cr 6 reference sample (B524) with CrKα radiation. Comparison of scans using 1 mm minilens primary optic (A) against 1 mm collimator (B) and of peak profiles from scintillation (C) and PSD (B) detector with collimator.

## 6. Summary

Charon XRD is a center-free large X-ray diffractometer for near-surface material 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 ±0.001° and linear positioning in one direction of ±0.01 mm.

Charon XRD offers a plurality of potential configuration levels such as upgrade with PSD or X-ray optics.

The following advantages over current conventional facilities are:

- 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.

## 7. References


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