# StressX:

# XRD Solution to Residual Stress Determination in Industrial Application Field

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GNR Analytical Instruments Group

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**G.N.R. Analytical Instruments Group** was established in 1984 in Milan, Italy.

**G.N.R. Analytical Instruments Group** designs and produces Optical Emission Spectrometers (OES) for the measurement of elemental composition of metal alloys and XRD/XRF Spectrometers for material structure and composition.

**G.N.R. Analytical Instruments Group** with a production of over 220 spectrometers/year is a leading company in the field of OES spark and XRD/XRF spectroscopy.

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Nr 50 100 4258 - Rev. 04

*Si attesta che / This is to certify that*

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**Progettazione, fabbricazione, assistenza e messa in esercizio di spettometri ad emissione ottica e strumentazione a raggi X per la caratterizzazione dei materiali. Commercializzazione di prodotti associati ed affini** (IAF 19, 29a)

***Design, manufacture, service and start-up of optical emission spectometers and x-ray instruments for materials characterization. Trade of complementary and similar product*** (IAF 19, 29a)

ACCREDIA

Per l'Organismo di Certificazione
*For the Certification Body*
TÜV Italia S.r.l.

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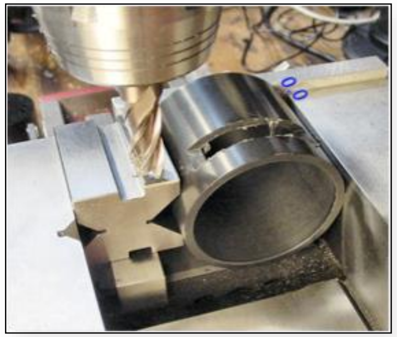
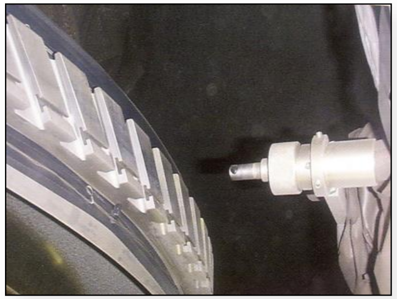
Origins of residual stresses in a component may be classified as:

**Mechanical, Thermal and Chemical**

Residual stresses can arise in materials at almost every process step:

- **Primary product** : casting, forming, forging, extruding, rolling, bending, etc.
- **Surface removal** : machining, electro-erosion, etc.
- **Joining** : welding, brazing, etc.
- **Mechanical surface treatments** : shot peening, laser shock, etc.
- **Heat treatments**: quenching, carburising, nitriding, carbonitriding
- **Chemical treatments**: PVD, CVD coatings, electro deposition, etc.





# Effects of Residual Stress

Residual stress plays an important role with respect to the operating performance of mechanical parts.

It affects material properties as:

- **fatigue**
- **fracture**
- **corrosion**
- **friction**

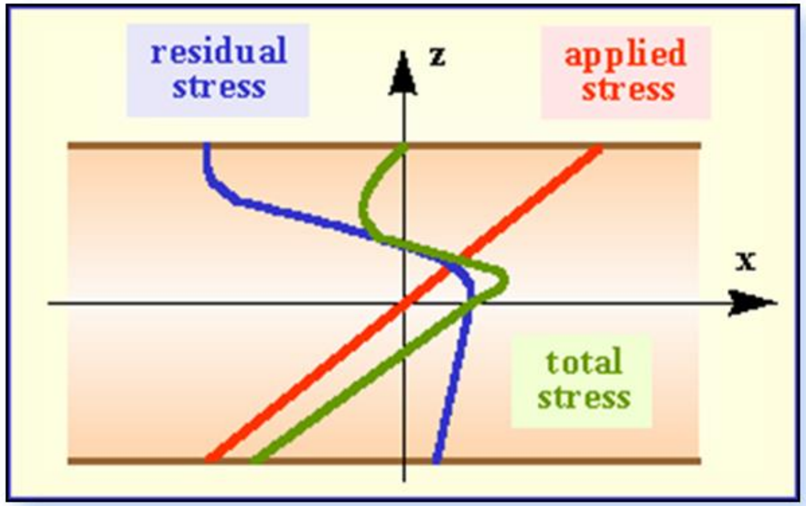
In some case, the residual stress induced by manufacturing processes can be predicted.

It remains often necessary to adjust the theoretical calculations through experimental results obtained by **XRD measurements.**

# Effects of Residual Stress

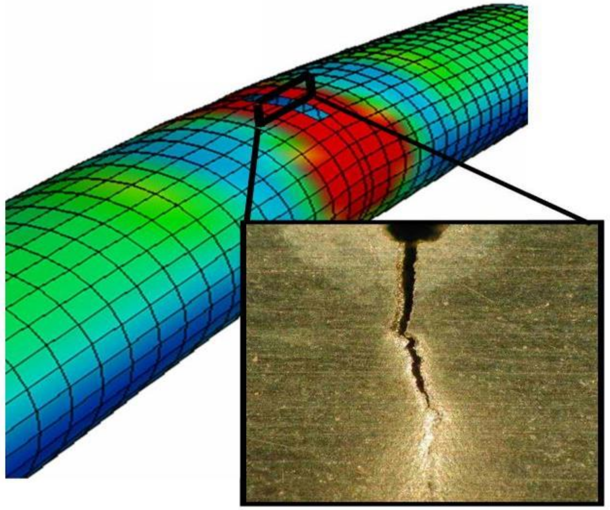
**Compressive** Residual Stress (**σ < 0**)

- Reduces **crack** propagation
- Prolongs **fatigue life** and **durability**
- Increases **strength** and **corrosion resistance**
- Decreases **total stress** in the areas where high loads are applied




**Tensile** Residual Stress (**σ > 0**)

- Increases **crack** propagation
- **Reduces the mechanical performance** of materials



# Reference samples: ASTM E915 and EN 15305

The calibration (alignment or zeroing) of the Robotic StressX is checked by two reference samples:

1. Zero-stress sample (iron powder): prepared as reported in ASTM E915

 (UNI EN 15305 constraints are larger than ASTM E 915)

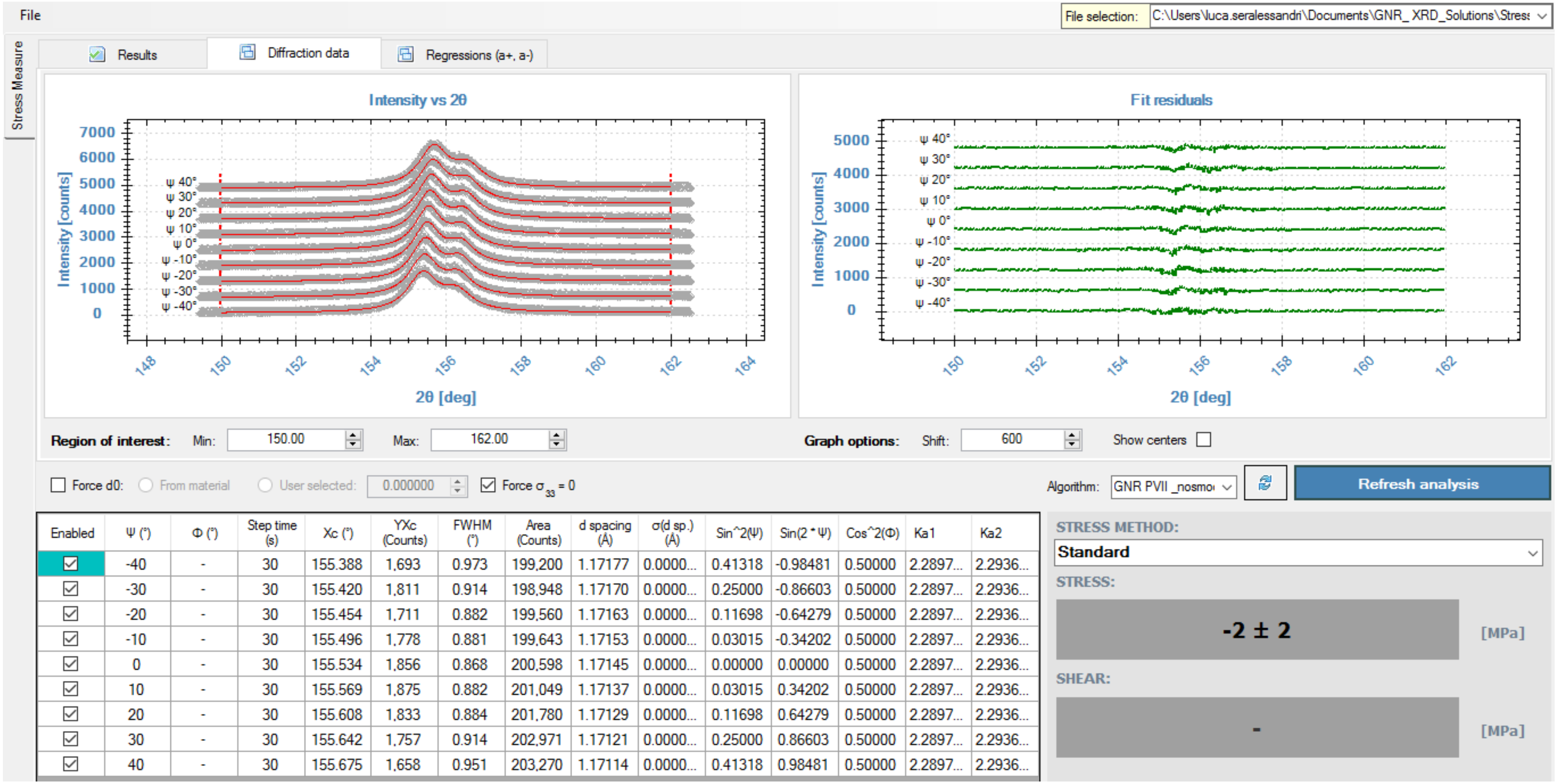
2. ILQ (Inter Laboratory Qualified) sample - GNR_Master: prepared as reported in UNI EN 15305

# Standard Method to verify alignment of X-ray diffractometer for residual stress measurements.

- Stress-Free Specimen preparation: iron powder with 1 < particle size < 45 μm mixed with binder.
- **Systematic Error:** average of five measurements must be within **14 MPa**.
- **Random Error:** standard deviation of five measurements should be within **7 MPa**.
- The accuracy of this method is considered to be absolute because the specimen is stress-free.

| File Name | Stress [MPa] | Average [MPa] | Std Dev [MPa] | ASTM E916 COMPLIANCE |
|---|---|---|---|---|
| stress_free_1 | -6 | **-3.9** | **5.9** | OK |
| stress_free_2 | -6 | | | |
| stress_free_3 | -1 | | | |
| stress_free_4 | -1 | | | |
| stress_free_5 | -6 | | | |
| stress_free_6 | -1 | | | |
| stress_free_7 | -9 | | | |
| stress_free_8 | -5 | | | |
| stress_free_9 | -13 | | | |
| stress_free_10 | 9 | | | |

# ASTM E915




| Enabled | Ψ (°) | Φ (°) | Step time (s) | Xc (°) | YXc (Counts) | FWHM (°) | Area (Counts) | d spacing (Å) | σ(d sp.) (Å) | Sin^2(Ψ) | Sin(2 * Ψ) | Cos^2(Φ) | Ka1 | Ka2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | -40 | - | 30 | 155.388 | 1,693 | 0.973 | 199,200 | 1.17177 | 0.0000... | 0.41318 | -0.98481 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | -30 | - | 30 | 155.420 | 1,811 | 0.914 | 198,948 | 1.17170 | 0.0000... | 0.25000 | -0.86603 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | -20 | - | 30 | 155.454 | 1,711 | 0.882 | 199,560 | 1.17163 | 0.0000... | 0.11698 | -0.64279 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | -10 | - | 30 | 155.496 | 1,778 | 0.881 | 199,643 | 1.17153 | 0.0000... | 0.03015 | -0.34202 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | 0 | - | 30 | 155.534 | 1,856 | 0.868 | 200,598 | 1.17145 | 0.0000... | 0.00000 | 0.00000 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | 10 | - | 30 | 155.569 | 1,875 | 0.882 | 201,049 | 1.17137 | 0.0000... | 0.03015 | 0.34202 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | 20 | - | 30 | 155.608 | 1,833 | 0.884 | 201,780 | 1.17129 | 0.0000... | 0.11698 | 0.64279 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | 30 | - | 30 | 155.642 | 1,757 | 0.914 | 202,971 | 1.17121 | 0.0000... | 0.25000 | 0.86603 | 0.50000 | 2.2897... | 2.2936... |
| ☑ | 40 | - | 30 | 155.675 | 1,658 | 0.951 | 203,270 | 1.17114 | 0.0000... | 0.41318 | 0.98481 | 0.50000 | 2.2897... | 2.2936... |

# UNI EN 15305: ILQ Inter Laboratory Qualified

## GNR ILQ Master Sample defined by Round Robin Procedure

| MASTER_GNR | Point | Stress X | Stress Tech | Seifert ID3003 PTS | Elphise Set-X | NN IS-StressX3000 | $\sigma_{ref}$ [MPa] | Std Dev | $R_\sigma$=2.8* Std Dev |
|---|---|---|---|---|---|---|---|---|---|
| C3 | A | -592 | -542 | -557 | -566 | -572 | -566 | 18.5 | 51.8 |
| | B | -617 | -584 | -620 | -648 | -581 | -610 | 27.9 | 78.1 |
| | C | -572 | -528 | -530 | -549 | -585 | -553 | 25.3 | 70.8 |

Sample name: Master C3

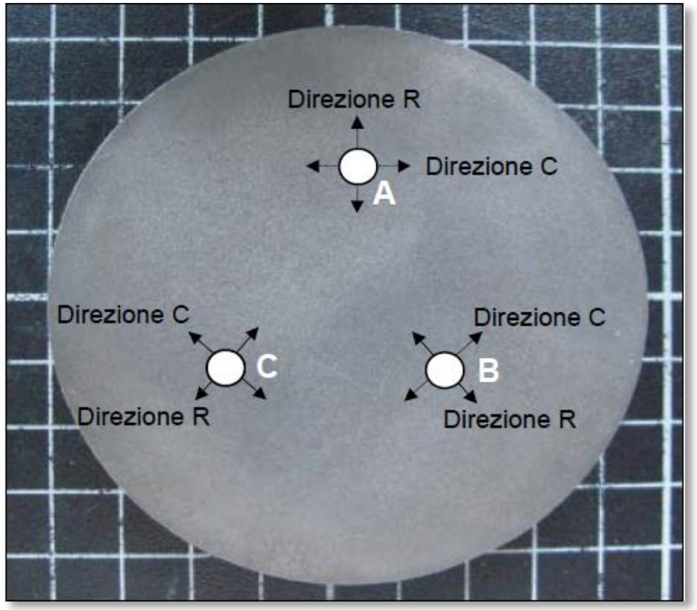
3 areas: A B C

Direction: circumferential (C)

$\sigma_{ref}$ = average stress over 5 instruments from 5 different labs

Std Dev = standard deviation over 5 measurements

$R_\sigma$ = reproducibility = 2.8*Std Dev



# UNI EN 15305: ILQ Inter Laboratory Qualified

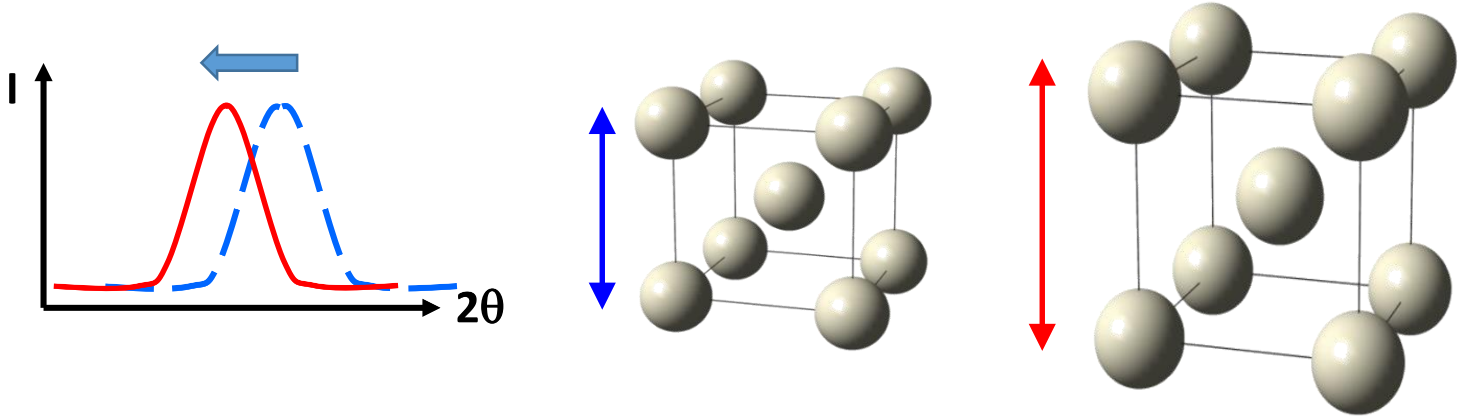
| STRESS X | Point | Stress | $\overline{\sigma}$ | Std Dev | $r_\sigma$ = 2.8*Std Dev | | $\lvert\sigma ref - \overline{\sigma}\rvert$ | CDσ | COMPLIANCE |
|---|---|---|---|---|---|---|---|---|---|
| C3 | A1 | -560 | -580 | 11.8 | 33.0 | | 13.8 | 30.1 | OK |
| | A2 | -586 | | | | | 40.2 | 47.3 | OK |
| | A3 | -577 | | | | | 21.4 | 42.0 | OK |
| | A4 | -588 | | | | | | | |
| | A5 | -587 | | | | | | | |
| | | | | | | | | | |
| | B1 | -648 | -650 | 16.1 | 45.0 | | | | |
| | B2 | -624 | | | | | | | |
| | B3 | -653 | | | | | | | |
| | B4 | -661 | | | | | | | |
| | B5 | -665 | | | | | | | |
| | | | | | | | | | |
| | C1 | -584 | -574 | 15.3 | 42.9 | | | | |
| | C2 | -580 | | | | | | | |
| | C3 | -549 | | | | | | | |
| | C4 | -587 | | | | | | | |
| | C5 | -571 | | | | | | | |

$$CD_\sigma = \frac{1}{\sqrt{2}}\sqrt{R_\sigma^{\,2} - r_\sigma^{\,2}\left(\frac{n-1}{n}\right)}$$

$$\left|\sigma_{ref} - \overline{\sigma}\right| \leq CD_\sigma$$

$$\overline{\sigma} = \frac{1}{n}\sum_{i=1}^{n}\sigma_i$$

- XRD measurement reliability depens on:
  - Degree of crystallinity
  - Surface roughness
  - Non-flat surfaces
  - Highly textured material
  - Coarse grained material
  - Multiphase materials
  - Overlapping diffraction lines
  - Broad diffraction lines

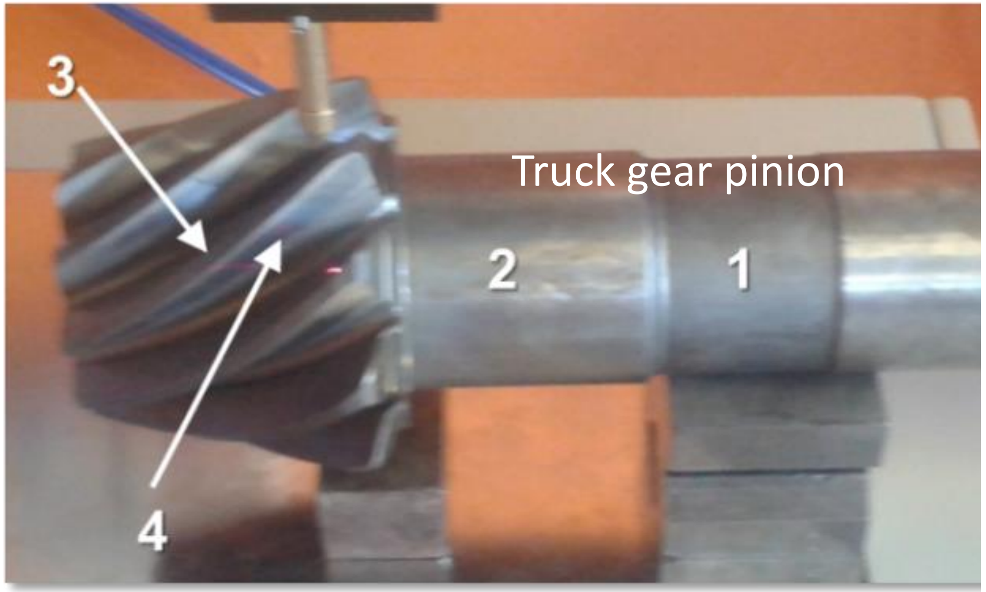


# StressX: Automation First


- 6-Axis anthropomorphic robot: accuracy and repeatability < 20 μ
- **Selectable radius: 120, 140, 160 mm (Omega-mode; Chi-mode)**
- Psi scan: programmable -45° / +45° with oscillations from 1° to 10°
- 2 Theta range: from 125° to 164°
- Cr, Co, Cu, Mn X-Ray Tube with mono or polycapillary collimation (120 μ)
- 300 W X-Ray Generator – Integrated Cooling System
- **1D Hybrid Photon Counting (HPC) microstrip speed detector**
- **Auto Alignment Laser System: accuracy < 2 μ**
- Compliance with ASTM E915 practice and UNI EN 15305
- Uni-axial, Bi-axial and Tri-axial stress state analysis
- Surface mapping with dynamic sections view
- High resolution USB Video Camera
- Custom Solutions

# Effects of grinding not properly performed

| AREA | TREATMENT | RS (MPa) |
|---|---|---|
| **1** | GRINDING | -236 ± 6 |
| **2** | SHOT PEENING | -648 ± 4 |
| **3** | SHOT PEENING + GRINDING: Burned | -316 ±13 |
| **4** | SHOT PEENING + GRINDING: not Burned | -561 ± 3 |

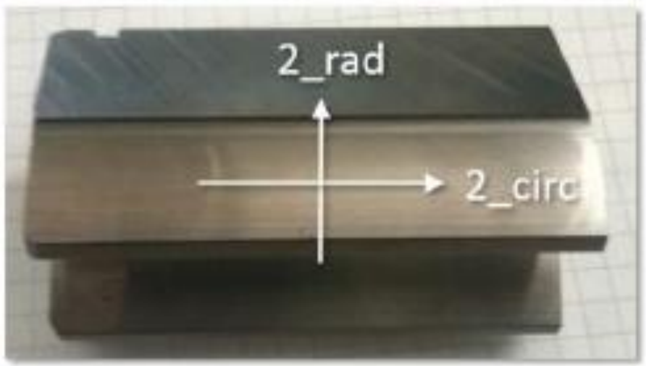


# Application: Transmission

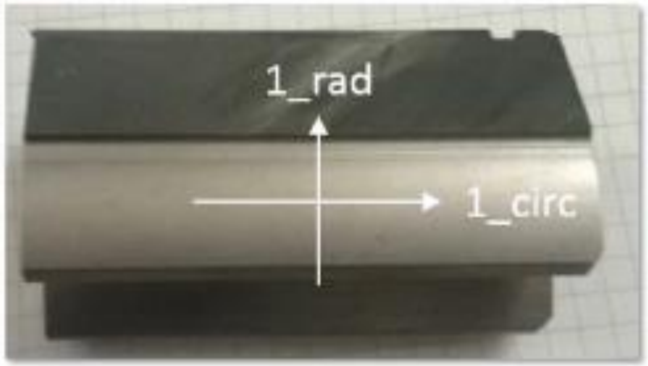
Measurement performed on pitch diameter of a gear.

Surface Finishing: before and after shot peening treatment process.

| Measuring Point | Residua Stress [MPa] |
|---|---|
| Sample 1_rad | -417 ± 13 |
| Sample 1_circ | -399 ± 12 |
| Sample 2_rad | -1267 ± 15 |
| Sample 2_circ | -1253 ± 12 |



Sample 2

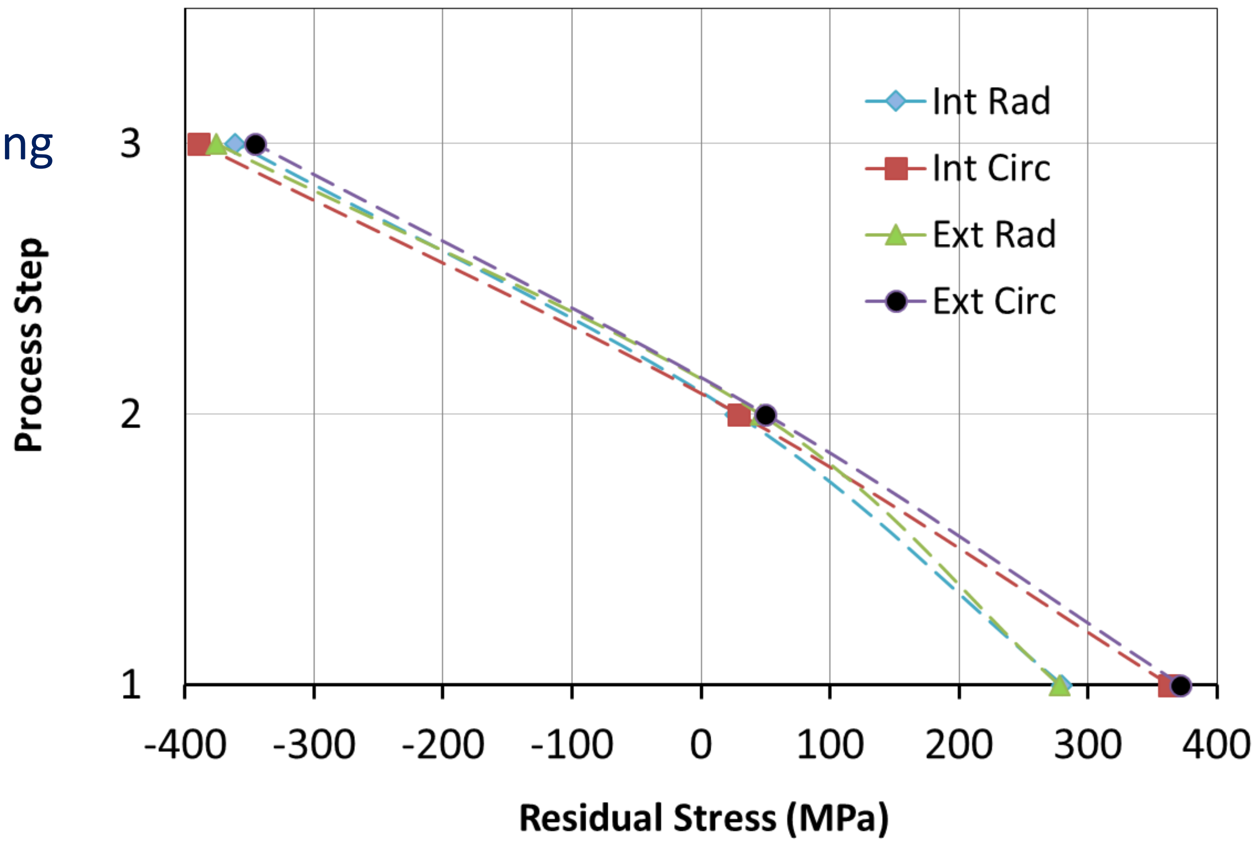


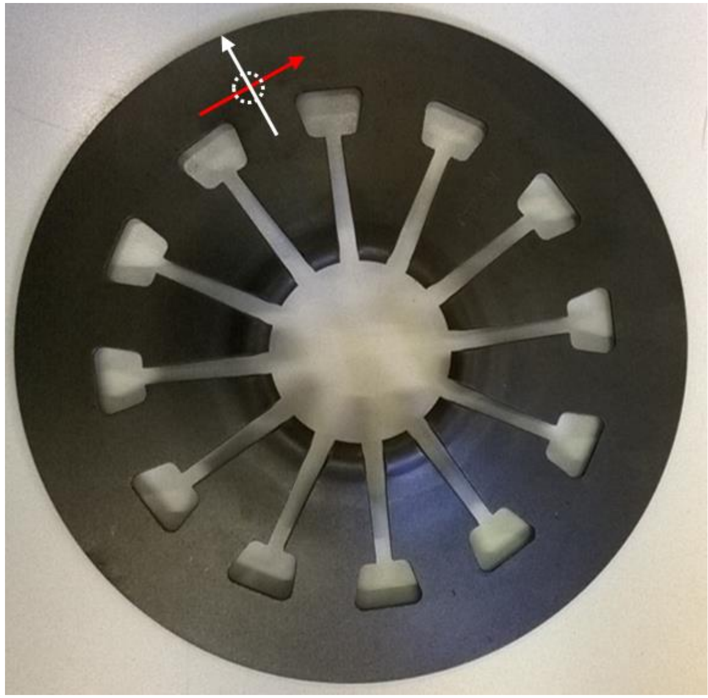
Sample 1

# Application: Clutch Manufacturing

## Diaphragm Spring

1. casting
2. induction hardening
3. shot peening

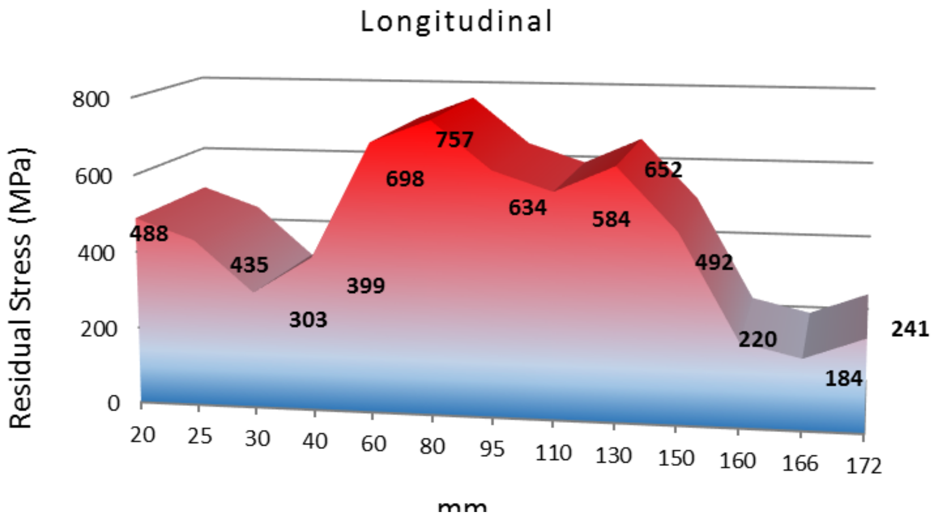


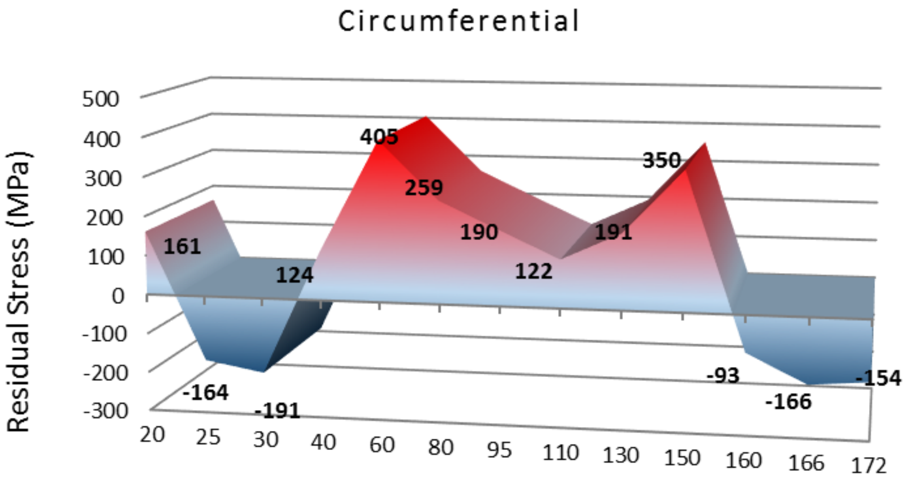



# Application: Weld Bead

## On site measurements: weld bead on mock-up of turbine shaft

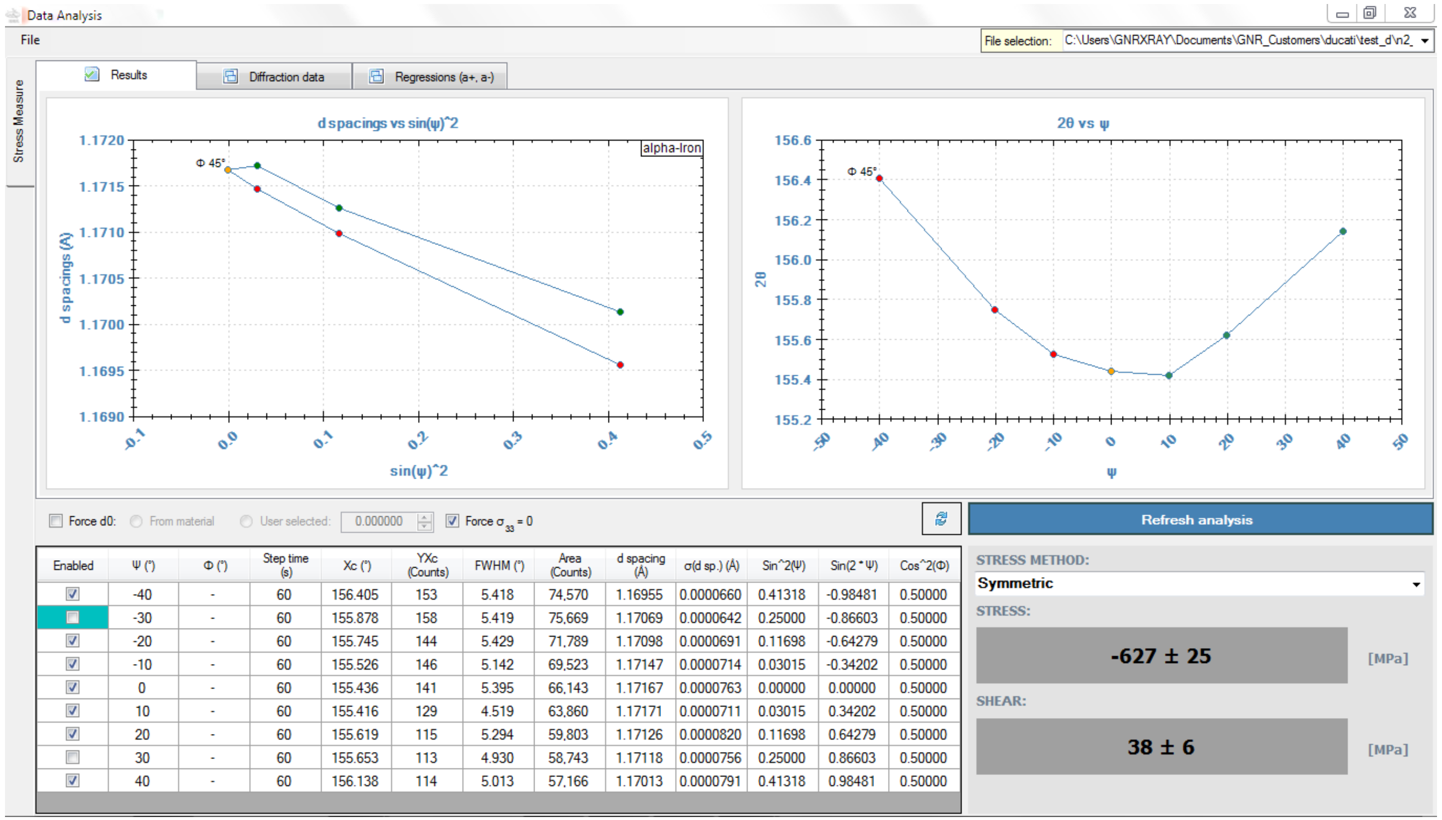

(by courtesy of FOMAS Group).



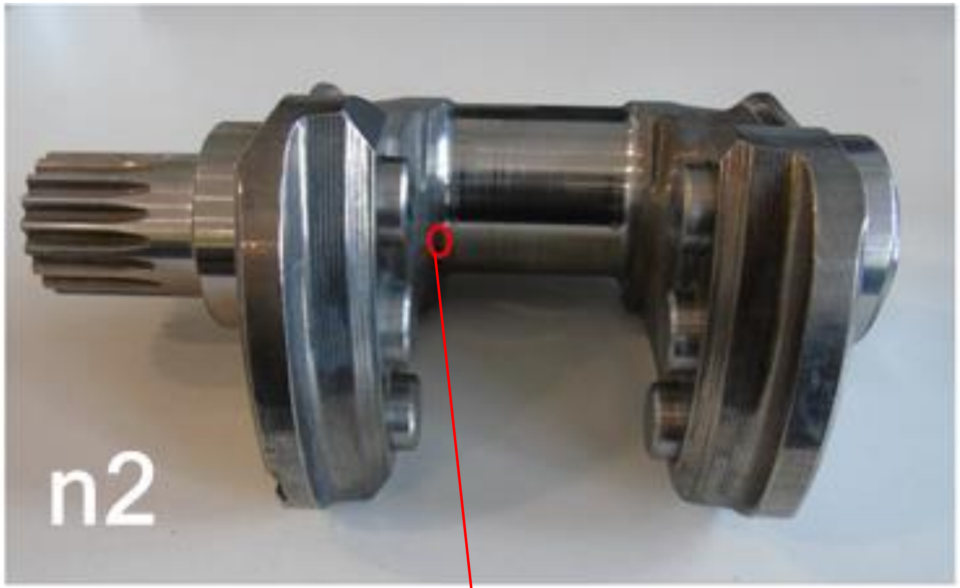



# Application: Complex Geometries

Crankshaft: laser alignment procedure and large goniometric radius (up to 160 mm) allow StressX to analyse complex mechanical component (shape and size) also in points traditionally difficult to be reached.

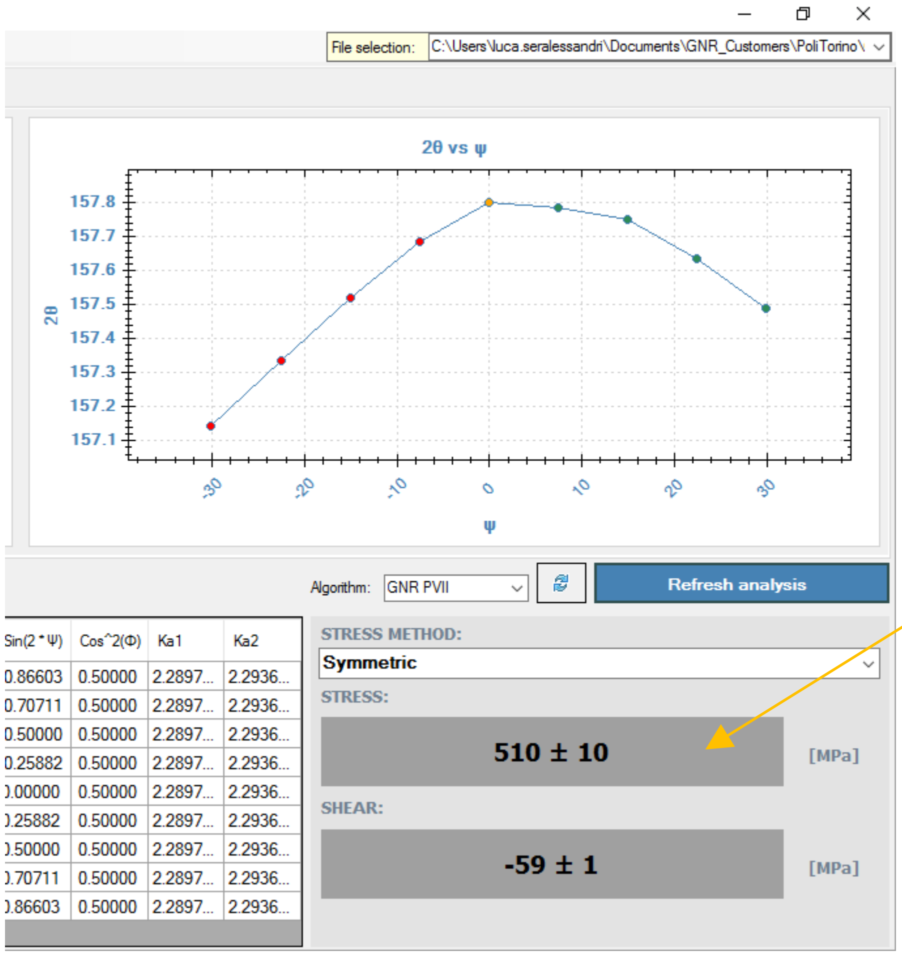


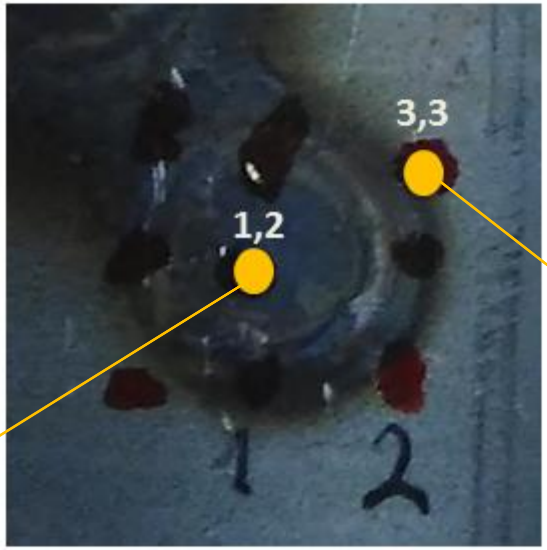

| Enabled | Ψ (°) | Φ (°) | Step time (s) | Xc (°) | YXc (Counts) | FWHM (°) | Area (Counts) | d spacing (Å) | σ(d sp.) (Å) | Sin^2(Ψ) | Sin(2*Ψ) | Cos^2(Φ) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ☑ | -40 | - | 60 | 156.405 | 153 | 5.418 | 74,570 | 1.16955 | 0.0000660 | 0.41318 | -0.98481 | 0.50000 |
| ☐ | -30 | - | 60 | 155.878 | 158 | 5.419 | 75,669 | 1.17069 | 0.0000642 | 0.25000 | -0.86603 | 0.50000 |
| ☑ | -20 | - | 60 | 155.745 | 144 | 5.429 | 71,789 | 1.17098 | 0.0000691 | 0.11698 | -0.64279 | 0.50000 |
| ☑ | -10 | - | 60 | 155.526 | 146 | 5.142 | 69,523 | 1.17147 | 0.0000714 | 0.03015 | -0.34202 | 0.50000 |
| ☑ | 0 | - | 60 | 155.436 | 141 | 5.395 | 66,143 | 1.17167 | 0.0000763 | 0.00000 | 0.00000 | 0.50000 |
| ☑ | 10 | - | 60 | 155.416 | 129 | 4.519 | 63,860 | 1.17171 | 0.0000711 | 0.03015 | 0.34202 | 0.50000 |
| ☑ | 20 | - | 60 | 155.619 | 115 | 5.294 | 59,803 | 1.17126 | 0.0000820 | 0.11698 | 0.64279 | 0.50000 |
| ☐ | 30 | - | 60 | 155.653 | 113 | 4.930 | 58,743 | 1.17118 | 0.0000756 | 0.25000 | 0.86603 | 0.50000 |
| ☑ | 40 | - | 60 | 156.138 | 114 | 5.013 | 57,166 | 1.17013 | 0.0000791 | 0.41318 | 0.98481 | 0.50000 |

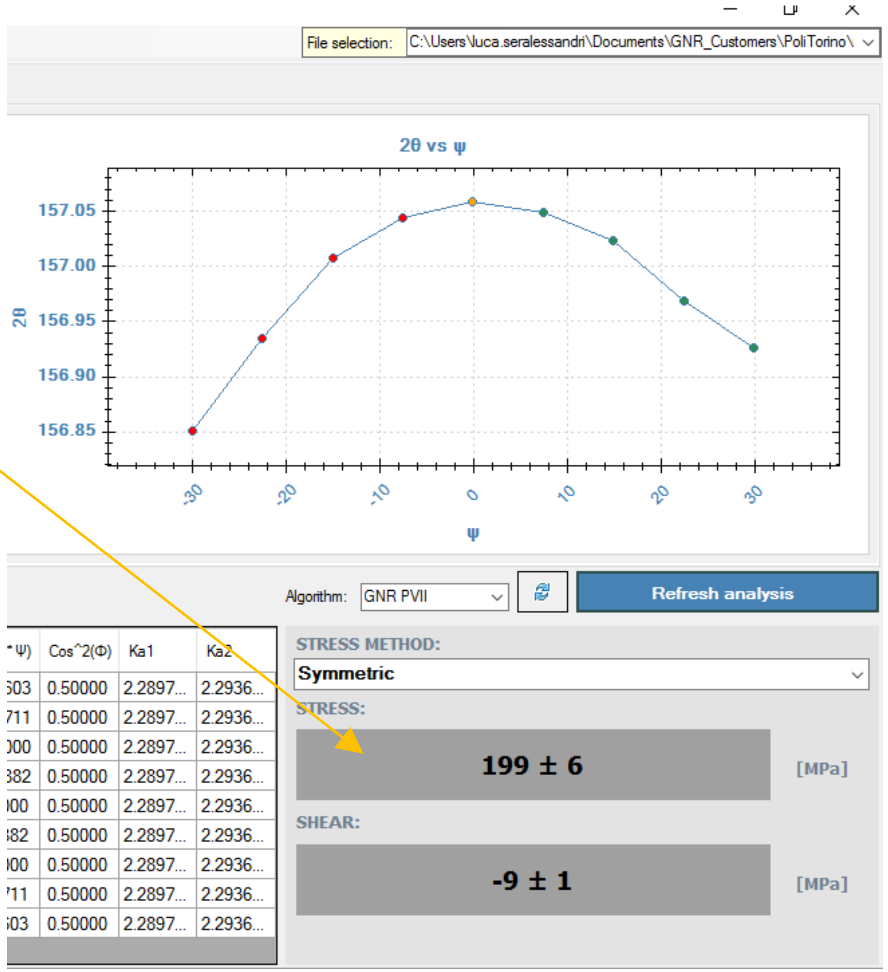



-627 ± 25 MPa

## Suspensions: increasing of the tensile residual stress to the center of the weld

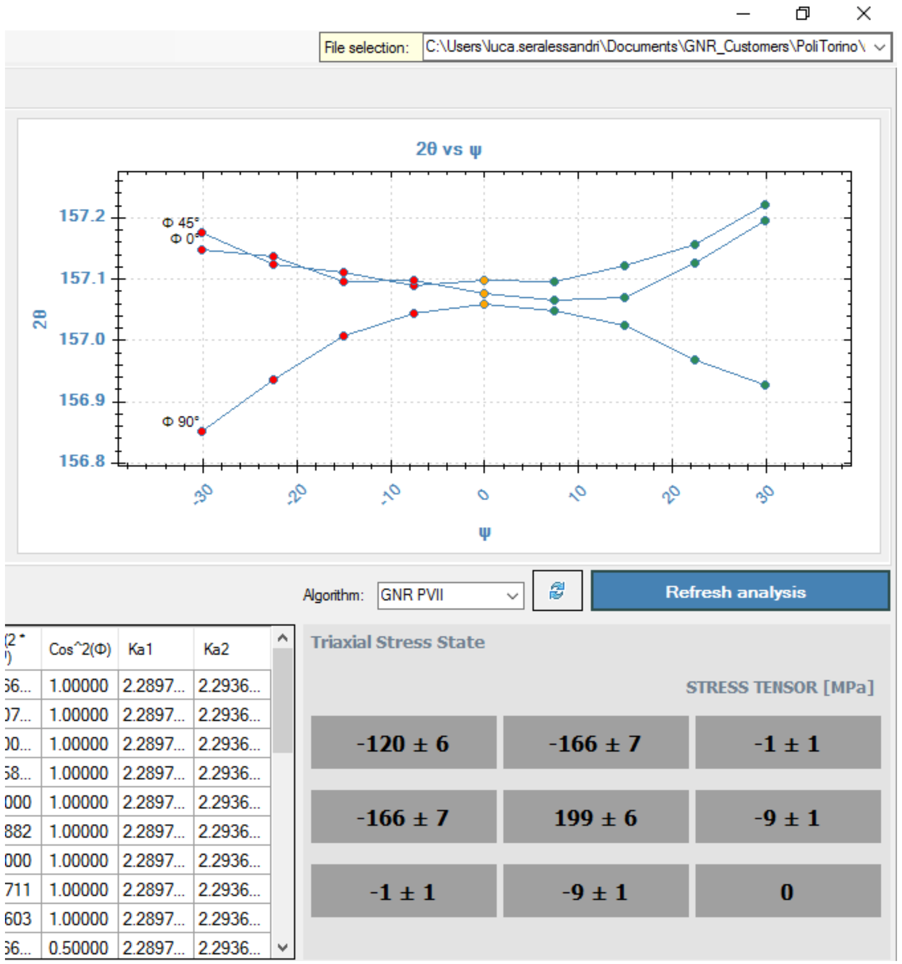


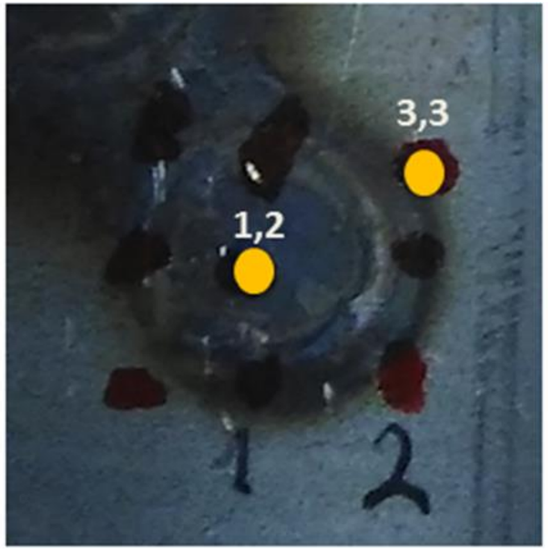



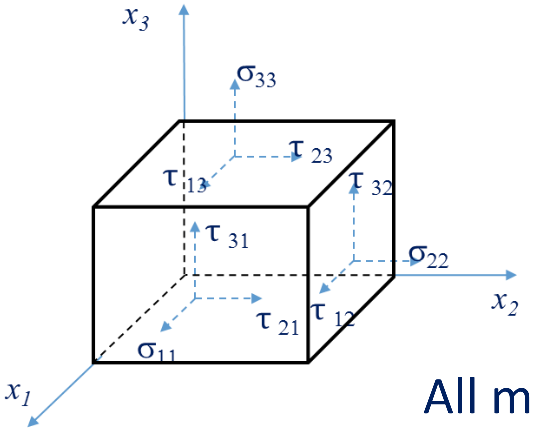



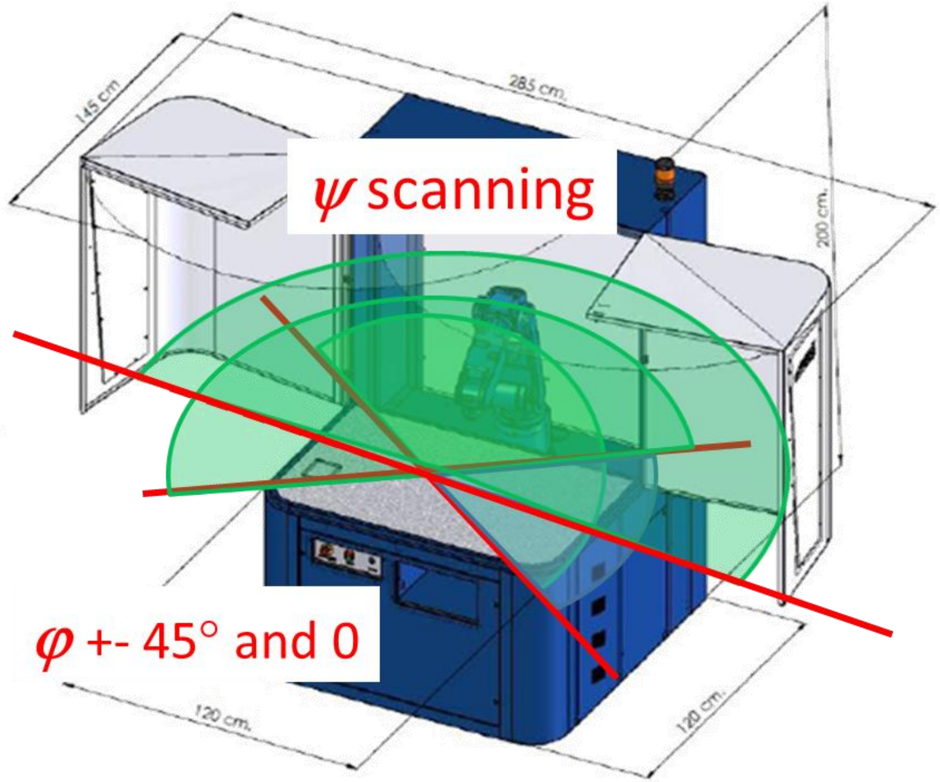
# Application: Tri-axial Measurements

Suspensions: tri-axial analysis of welding, residual stress tensor as input for finite element simulations.



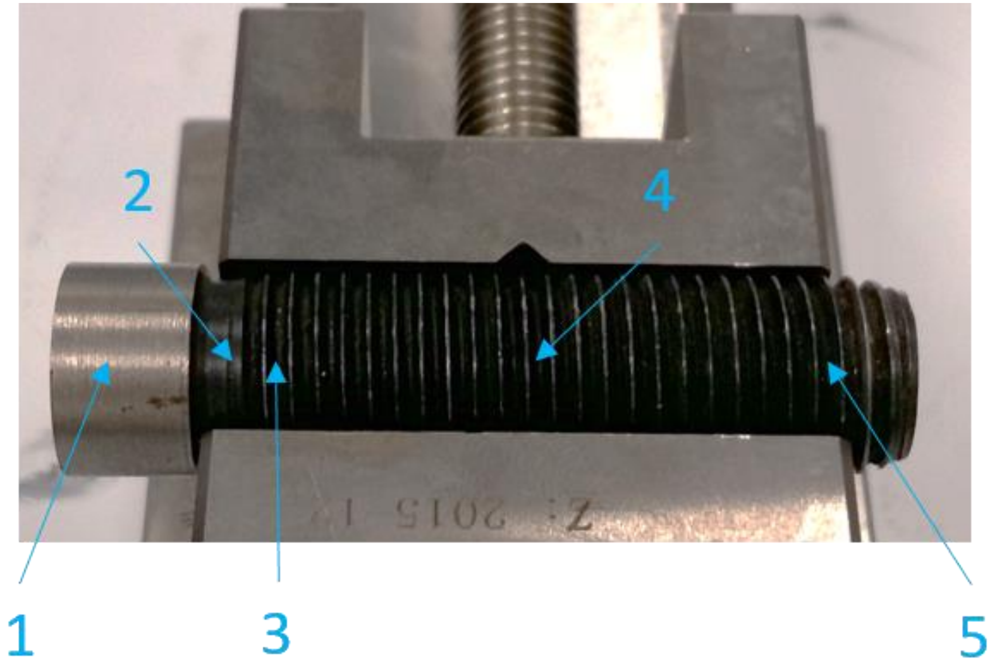




All matrix components

# Application: Curved Surfaces

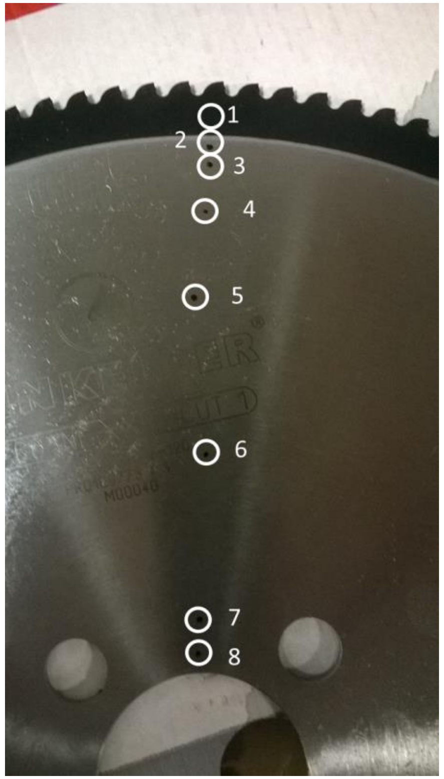
Screws Threads measured using polycapillary lens (diam: 120 μ)

| Sample | Measured points | RS (MPa) | Err (MPa) |
|---|---|---|---|
| M16 pitch diam. 4mm | 1 | -301 | 11 |
| | 2 | -43 | 3 |
| | 3 | -40 | 4 |
| | 4 | -49 | 3 |
| | 5 | -79 | 5 |



# Application: Comparing Performances

## Saw Blades




| Measuring Point | Stress (MPa) | Err |
|---|---|---|
| 1 | -231 | 7 |
| 2 | -318 | 5 |
| 3 | -291 | 4 |
| 4 | -175 | 4 |
| 5 | -69 | 4 |
| 6 | -48 | 4 |
| 7 | -65 | 5 |
| 8 | -88 | 5 |

| Measuring Point | Stress (MPa) | Err |
|---|---|---|
| 1 | -144 | 9 |
| 2 | -122 | 8 |
| 3 | -128 | 4 |
| 4 | -183 | 4 |
| 5 | -65 | 4 |
| 6 | -81 | 4 |

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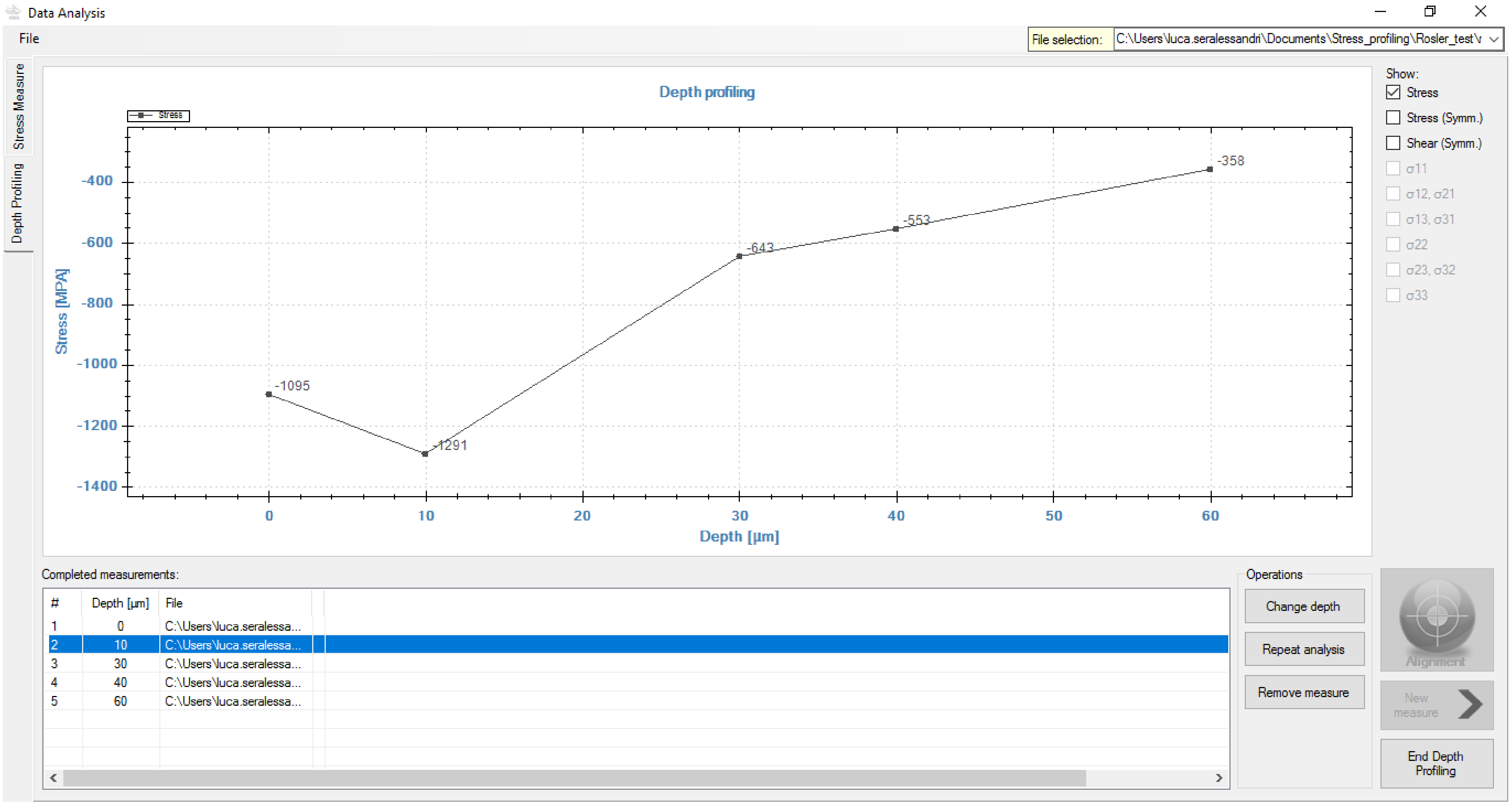
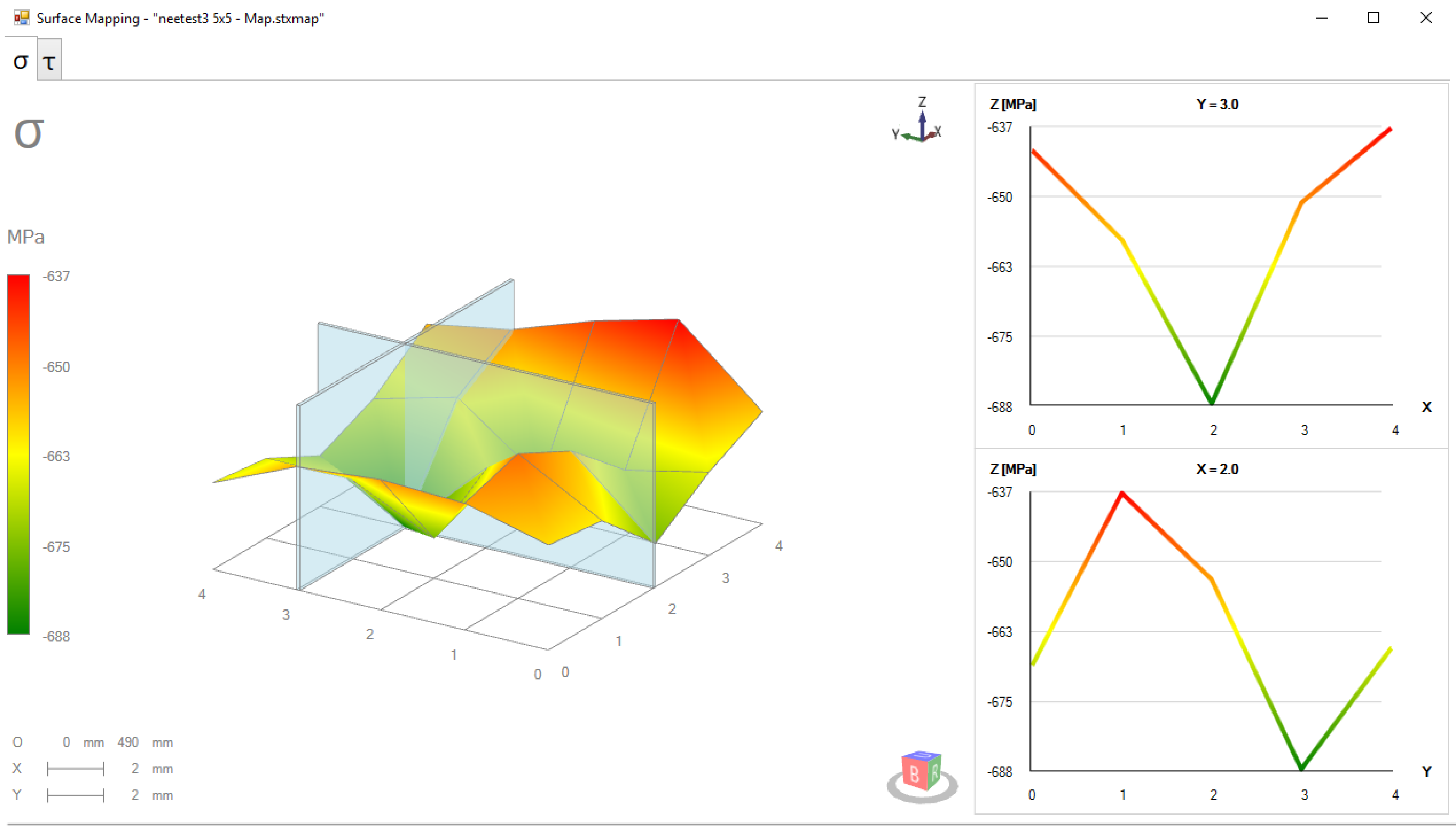
# StressX: Depth Profiling GUI




# StressX: Residual Stress Mapping with Dynamic Sections View




# SpiderX: Portability First

- High portability: < 19 Kg
- Batteries autonomy: 2 hours
- Radius: 70 mm
- Psi scan: programmable -45° / +45°
- 2 Theta range: from 135° to 165°
- Cr, Co, Cu, Mn X-Ray Tube with mono capillary collimation
- 4 W X-Ray Generator
- 1D Hybrid Photon Counting (HPC) microstrip speed detector
- Manual alignment assisted by laser: repeatability < 4 $\mu$
- Compliance with ASTM E915 practice and UNI EN 15305
- Uni-axial, Bi-axial and Tri-axial stress state analysis

# Conclusions

- Residual stresses can arise in materials at almost every process step.
- Compressive residual stress increases the fatigue life delaying crack initiation and propagation.
- Tensile stress reduces the mechanical performance of materials.
- X-ray diffraction is a non destructive method that allows to control and optimize the process.
- StressX and SpiderX are the GNR XRD solutions in agreement with EN 15305 and ASTM E915.

# Some references

RÖSLER finding a better way ...

Avio Aero A GE Aviation Business

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