# Organizational information

- All participants' **microphones** are **muted** during the webinar.

- Please do not forget to **activate** your PC **speakers** to enable **audio** or connect **headphones** to your PC.

- Please use the '**Questions and answers**' window, if you have any questions. We will answer questions at the end of the presentation.


- We will email the presentation to you after the webinar.

- The webinar is recorded and will soon be made available on our website.

# CALCULATING RESIDUAL STRESSES FROM THE MEASURED STRAIN

**Alessio Benincasa**
**SINT Technology srl - HBM partner**
**Calenzano, Florence - Italy**

# Speaker

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  Sales & Product Manager
  SINT Technology srl

- Degree in mechanical engineering

- 13 years experience in
  SINT Technology

- 11 years experience in the
  residual stress field

- 8 years experience as Product Manager
  of the MTS3000

- Certified at 3rd level as strain gage expert

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# Summary

- Who is SINT Technology
- Nature and Source of Residual Stresses
- Main Strain Gage Methods for Residual Stress Measurements
- Hole Drilling Method
- Starting Point: the Measured Strains
- The ASTM E837 Standard
- Other Calculation Methods & Comparison
- Typical Measurement Uncertainty
- Practical Examples - Some Typical Test Results
- Q&A

# Who is SINT Technology – General info

HBM

SINT Technology is located in Calenzano, near **Florence**. The company was founded in 1990.

SINT Technology has **50 employees**. Most of them are engineers with average age of about 35 years.

The company turnover is about **4 M€**.


ilac-MRA

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LAB N° 0910

*Laboratory authorized by the Italian Ministry of Innovation, of University and Research (D.M. n° 593 / 2000, art.14). Accredited Test Laboratory (ISO / IEC 17025) - DNV Quality Certification n° 02678-98-AQ-FLR-SINCERT*

CERTIFICAZIONE DI SISTEMA DI GESTIONE
DNV·GL
ISO 9001 = OHSAS 18001

SINT Technology is **accredited test lab** for residual stress measurements

# SINT Technology - Main business activities

**Measurement Services**:

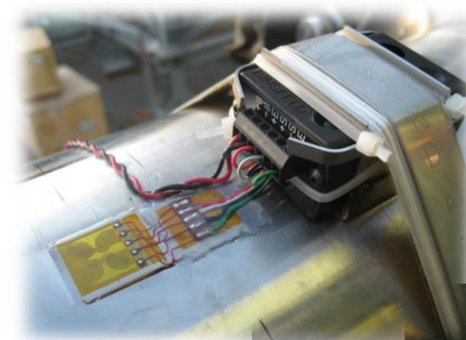
- Sound Intensity, Vibrations
- Experimental and residual stress analysis
- Power plant performance tests

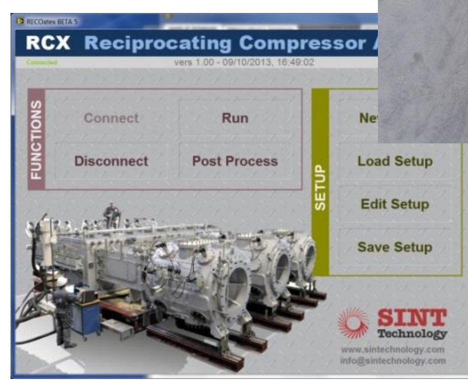
**Production of measuring equipments:**

- Restan-MTS3000 for RS measurements
- DRMS Cordless
- Custom products

**Design engineering**

**Software solutions**



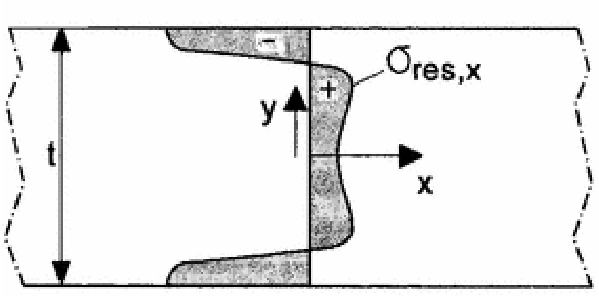


# Nature and Source of Residual Stresses

Residual stresses can be created from many different sources (and their combination). Generally, any process that causes **misfits** among different parts of a material will induce residual stresses. The main **sources** can be described in terms of the following categories:

- **Surface Machining** during component manufacture (e.g. turning, milling)
- **Surface Treatments** for changing near-surface stresses (e.g. shot / laser shock peening)
- **Bulk component misfit** in redundant structures (e.g. bridges, railway rails)
- **Non-Uniform Plastic Deformation** (e.g. material forming and shaping)
- **Thermal Effects** (e.g. solidification steps, welding, quenching)
- **Chemical and Phase Change** (connected also with the point above)

Residual stresses are **self-balanced** within the component: it means that, without the presence of any external load, the effect of the tensile areas balance those of the compressive areas to give zero force and moment resultants.




$$\int_{-t/2}^{t/2} \sigma_x \cdot dy = 0$$

**FORCE EQUILIBRIUM**

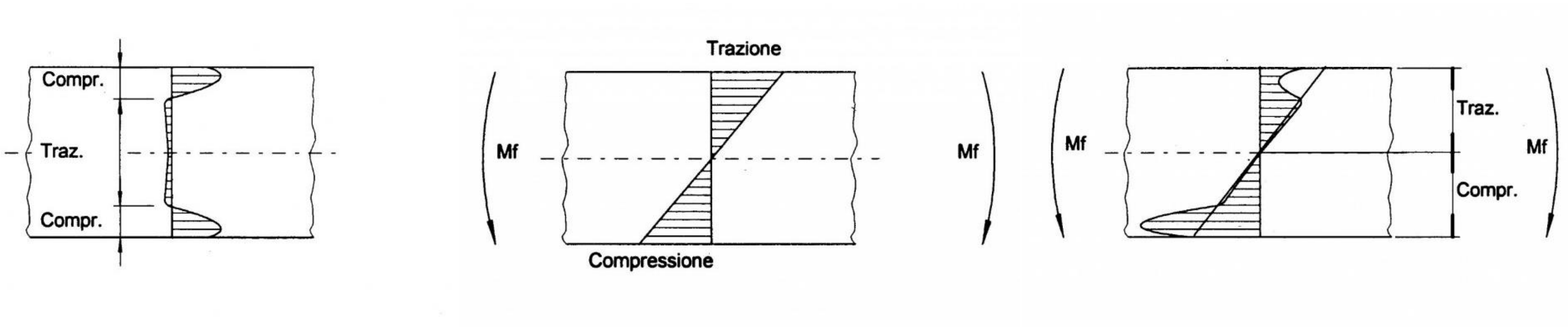
$$\int_{-t/2}^{t/2} y \cdot \sigma_x \cdot dy = 0$$

**MOMENT EQUILIBRIUM**

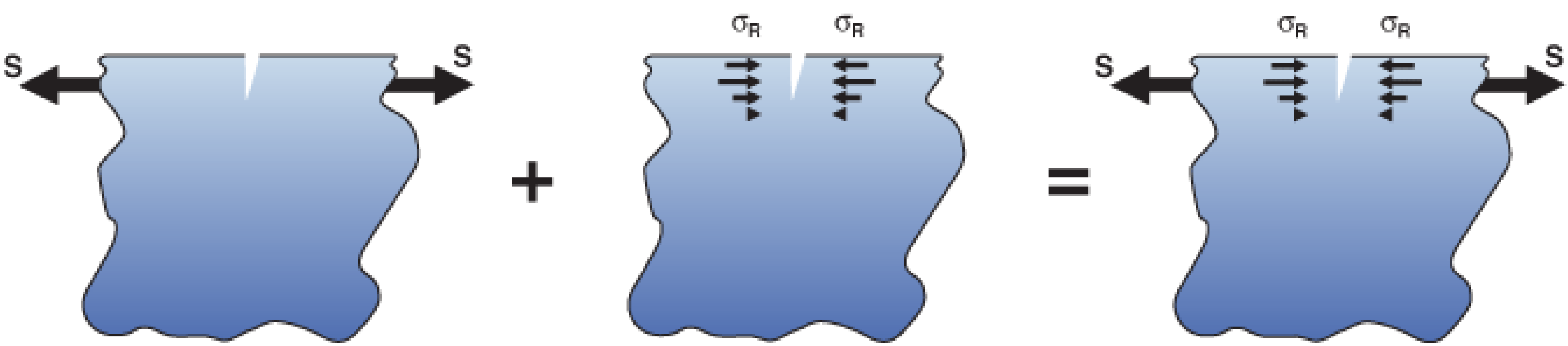
# Nature and Source of Residual Stresses

The **total** load experienced by the material at a given location within a component is equal to the **residual** stress (locked-in stresses) plus the **applied** load:

$$\sigma_{TOTAL} = \sigma_{RS} + \sigma_{EXT}$$

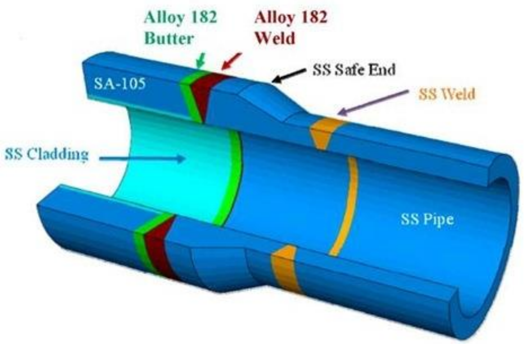


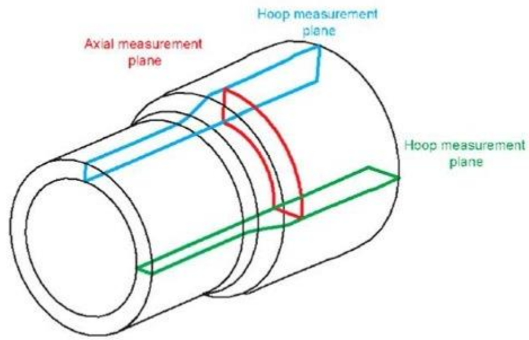

| Residual Stress (e.g. Shot Peening) | External Load (e.g. Bending) | Total Load |
|---|---|---|



# Main Strain Gage Methods for Residual Stress Measurements

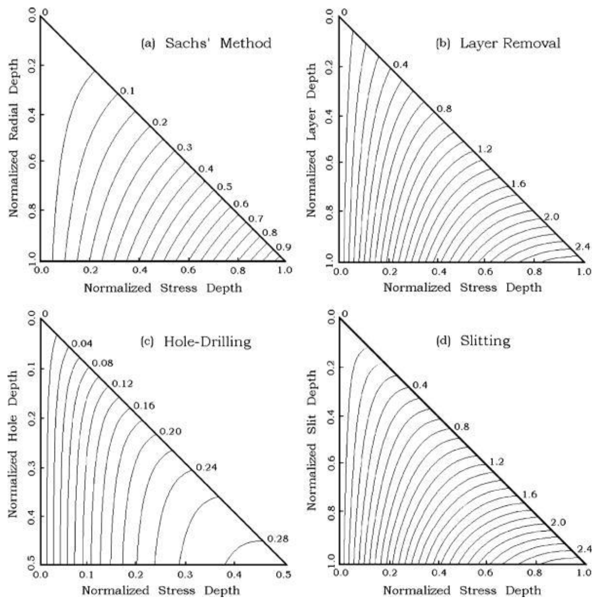
The **mechanical relaxation methods** for measuring residual stresses generally use **strain gages** to measure the **deformation change** that occurs in the given specimen.



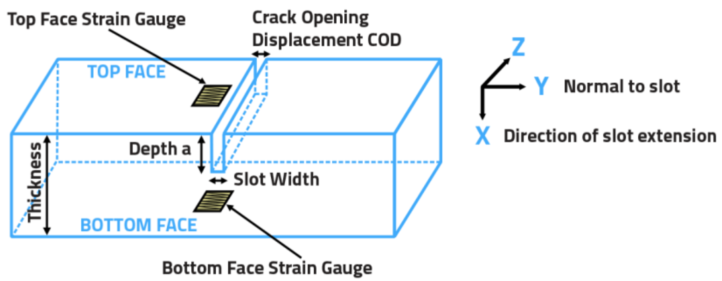

This deformation change is realized by cutting or **removing material**. The residual stresses in the remaining material then **redistribute** themselves so as to re-establish internal force equilibrium.

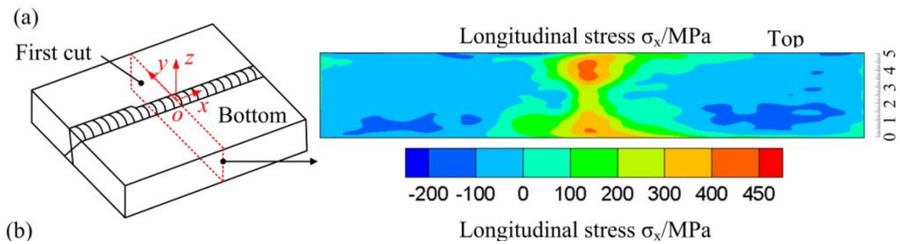
The **deformations** associated with this stress redistribution provide the data from which to **evaluate** the originally existing residual stresses. Since the material cutting locally reduces the original residual stresses, the various procedures used are called “relaxation” methods.

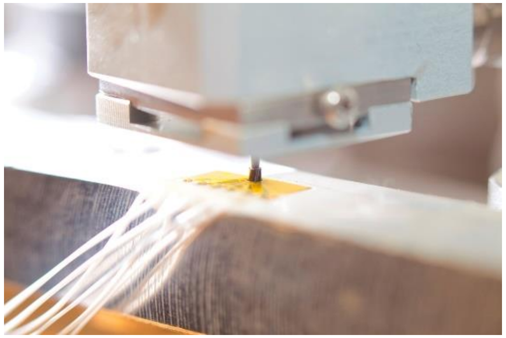


# Main Strain Gage Methods for Residual Stress Measurements

- ✓ Excision Method
- ✓ **Slitting Method**
- ✓ Two-Groove Method
- ✓ **Sectioning Method**
- ✓ Splitting Method
- ✓ **Ring-Core Method**
- ✓ Layer-Removal Method
- ✓ **Hole-Drilling Method**
- ✓ Deep-Hole Method

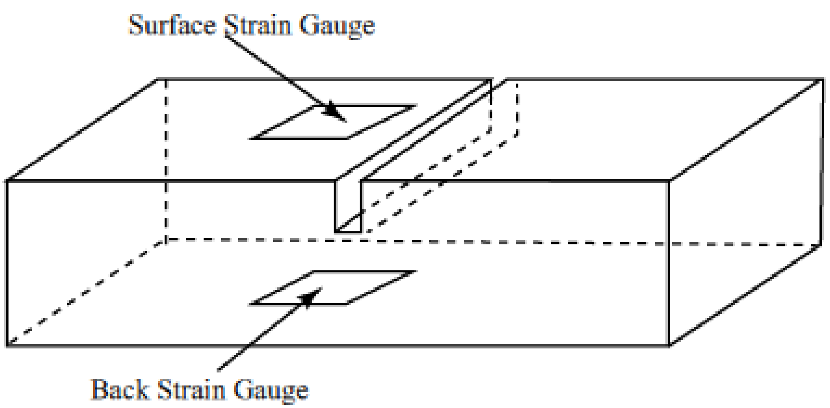


# Example - Slitting Method

In this method, relieved strain measurements are sequentially made as **slot cutting** proceeds in a series of small incremental **steps**. The strain gauge position is not limited to being on the specimen top surface. Other locations are also useful, notably on the opposite surface of the material specimen. As a general rule-of-thumb, strain measurements are most sensitive to nearby stresses. Thus, the **top and bottom** surface strain gauges are useful for determining stresses near their respective locations, thereby achieving better spatial coverage.




$$\varepsilon(h) = \int_0^h A(H, h)\,\sigma(H)\,dH$$

Where:

**ε(h)** is the measured surface strain when the slit reaches a depth h

**σ(H)** is the normal stress at depth H

**A (H,h)** is a compliance function determined by finite element calculations

This is an **"inverse" equation** that substantially complicates the required solution procedure and causes the stress results to be sensitive to the presence of small strain measurement errors. Sophisticated **mathematical procedures** are required to get reliable stress solutions.

The Slitting Method and Equation provide a conceptual **prototype** for the majority of the **relaxation type** of residual stress measurement methods.

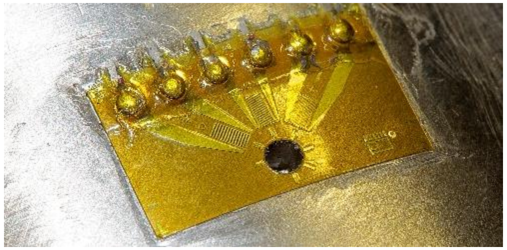
# Hole-Drilling Method

**Similar** in concept to the **Ring-Core** Method, but with **reversed geometry**.

The Hole-Drilling Method is by far the more **widely used**, possibly also the most widely used among all the residual stress measurement methods.

Main **reasons**:

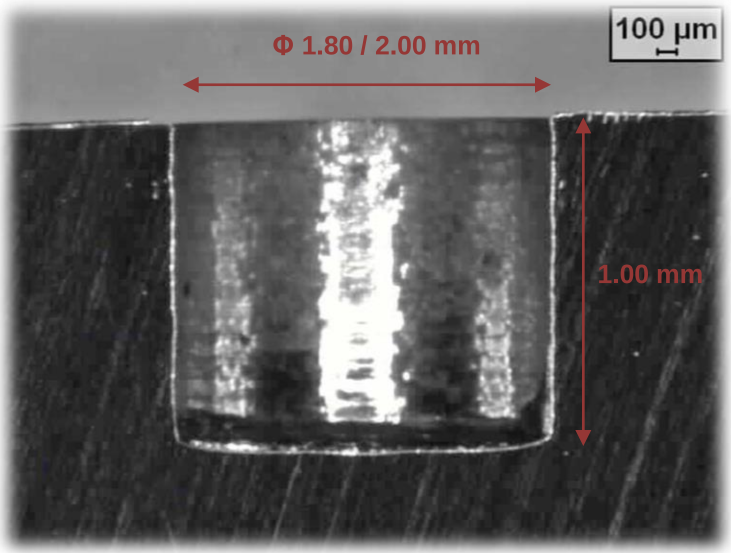
- ✓ **Reliability** of the results
- ✓ **Wide range** of applicable materials
- ✓ Simple, **fast** and flexible
- ✓ Semi-destructive (small hole)
- ✓ Availability of an **ASTM Standard**
- ✓ Modest **cost** of the equipment
- ✓ Wide range of strain gages



# Hole-Drilling Method

The hole drilling method consists in drilling a **small hole (approx. 1.8 mm x 1.0 mm)** into the center of a special 3-element strain rosette.

The hole changes the initial strain allowing **redistribution** of the internal stresses originally existing in the material.




To avoid inducing new stresses into the material during the drilling process, it is highly recommended to use the **high-speed drilling** technique (up to 400,000 RPM).

# Hole-Drilling Method

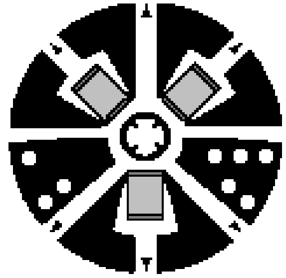
In the Hole-Drilling Method, strain gage rosette diameter ($D_{GAGE}$), hole diameter ($D_0$) and depth of analysis (z) are strongly connected and have to be scaled together.

**STRAIN GAGE DIAMETER $D_{GAGE}$**

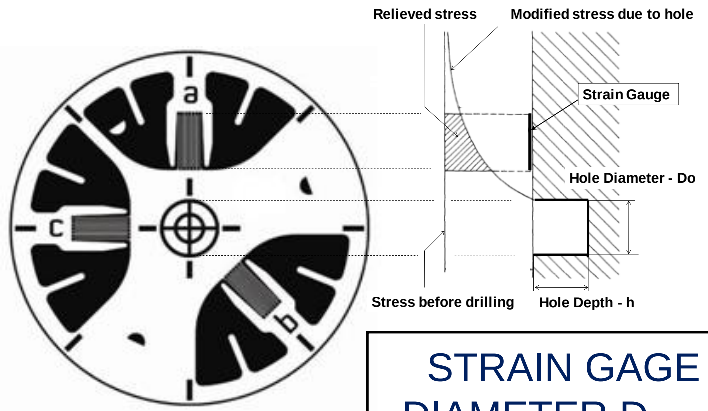
**$D_{GAGE}$ 2.55 mm**

**$D_{GAGE}$ 5.10 mm**

**$D_{GAGE}$ 10.20 mm**



Suppliers of strain gage rosette can provide strain gage in different sizes




**HOLE DIAMETER ($D_0$)**

**DEPTH (z)**

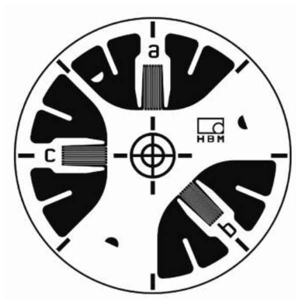
These parameters are mutually connected with the sensibility of the strain gage rosette

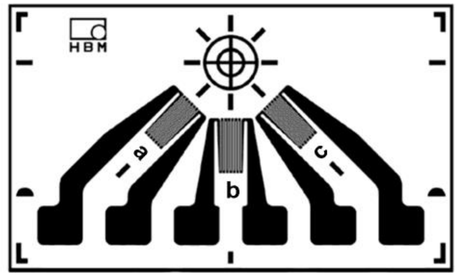
STRAIN GAGE DIAMETER $D_{GAGE}$

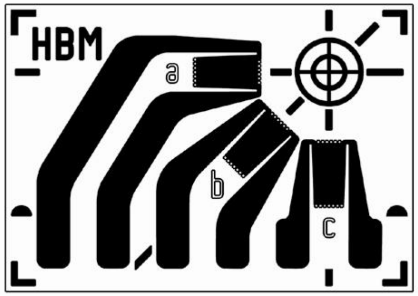
| | |
|---|---|
| HOLE DIAMETER ($D_0$) | 0.3–0.5*$D_{GAGE}$ |
| DEPTH (z) | Max. 0.2*$D_{GAGE}$ |

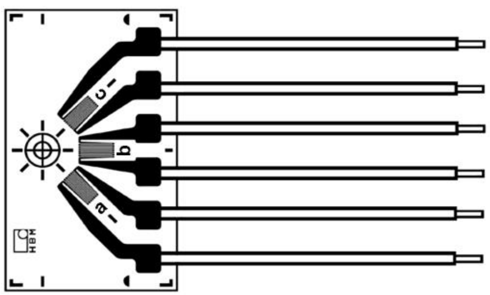
# Starting Point: the Measured Strains

Main types of **strain gages** for residual stress analysis:

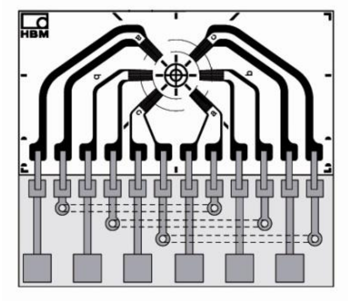


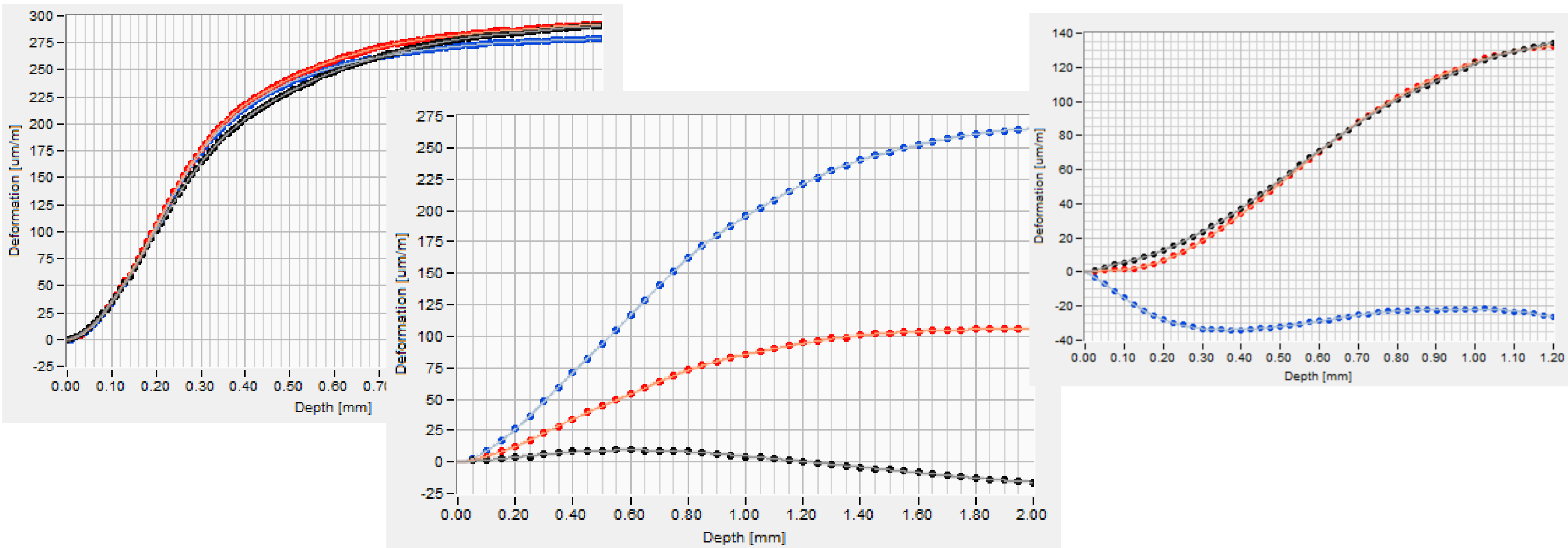




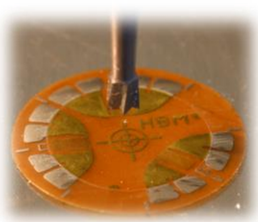

- Different types of strain gages, for **different test layouts** (i.e. near an edge or a corner)
- All the strain gages for residual stress analysis have at least **3 grids**, because for each depth a set of 3 data is required
- Additional grids can be used for **eccentricity** or **plasticity** correction

# Starting Point: the Measured Strains

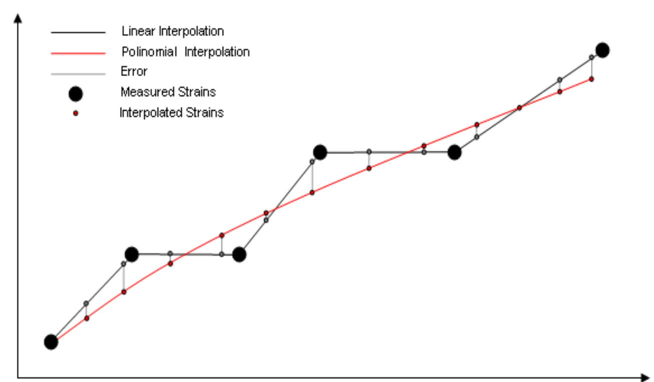
A **good and precise acquisition** of the **strains** that are released during the drilling process is the best starting point for the calculation of the results.




It's also possible to introduce an **interpolation** of the results, to reduce the small fluctuations and the random errors of the strain gages during the drilling process



| | Interp Type | Optimiz | Order/% | Visible | Residue |
|---|---|---|---|---|---|
| Strain | Spline | ☐ | 30 | ☑ | 1.06 |
| Strain 2 | None / Polinomial / ✓ Spline | ☐ | 30 | ☑ | 1.235 |
| Strain 3 | | ☐ | 30 | ☑ | 0.3884 |
| Strain 4 | Spline | ☐ | 30 | ☑ | 0 |



# Hole-Drilling Method – ASTM E837 Standard

The hole-drilling strain-gage method is the only method for calculating residual stress that is **STANDARDIZED** at world level (**ASTM E837**).

The first version of this standard dates back to 1995, the latest upgrade is available from the end of 2013.

ASTM INTERNATIONAL

**Designation: E837 – 13a**

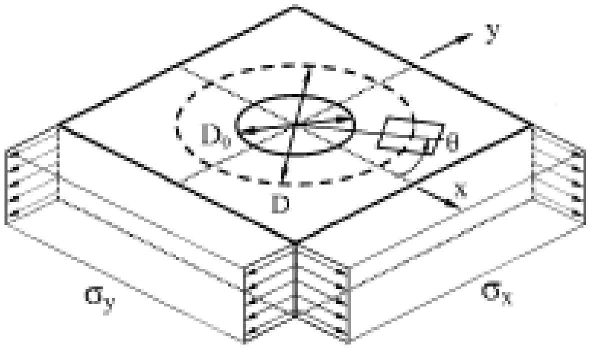
**Standard Test Method for**
**Determining Residual Stresses by the Hole-Drilling Strain-Gage Method[1]**

Standard ASTM E837-13 describes:

- Established **experimental** and **analytical** procedures for **reliable** residual stress evaluations
- **Limit of applicability** of the method
- The total drilling / analysis **depth** and the applicable **calculation algorithms**
- The number of **drilling increments** required
- The **numerical coefficients** for determining the value of residual stresses

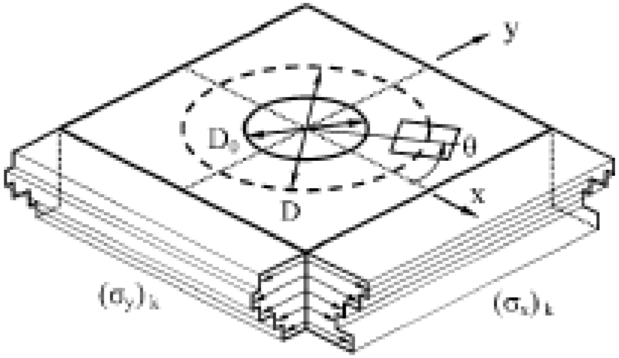
Definition of the calculation strategy of the standard ASTM E837-13:

## UNIFORM STRESS FIELD CALCULATION




- Stresses are assumed to be **uniform** in the entire drilling depth.
- Suitable for **Through** and **Blind** hole type.
- In case of **Blind Hole Type** this calculation is appropriate when **prior information** is available or for determining a **representative size** of the residual stresses that are present.

## NOT UNIFORM STRESS FIELD CALCULATION




- Stresses are assumed to be **not uniform** in the entire drilling depth.
- Plot of residual stress up to the total calculation depth (principal stresses and principal angle)

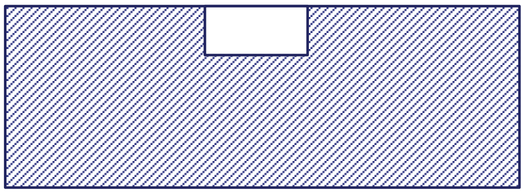
# ASTM E837-13: Thin / Thick workpiece

Different types of holes, based on the workpiece thickness:

## THROUGH HOLE - THIN WORKPIECE

- Workpiece thickness **<0.2·DGAGE** (std. 1mm)
- Stresses are considered **uniform** over the drilling depth
- Drilling depth: entire thickness
- Acquisition of a set of 3 strain values once the through hole is completed

## BLIND HOLE - THICK WORKPIECE



- Workpiece thickness **between 0.2·DGAGE and DGAGE** (std. between 1mm and 5mm).
- Thickness higher than **DGAGE**
- Stresses are assumed to be **uniform** or **not uniform.**

# ASTM E837-13 Extended: Step distribution

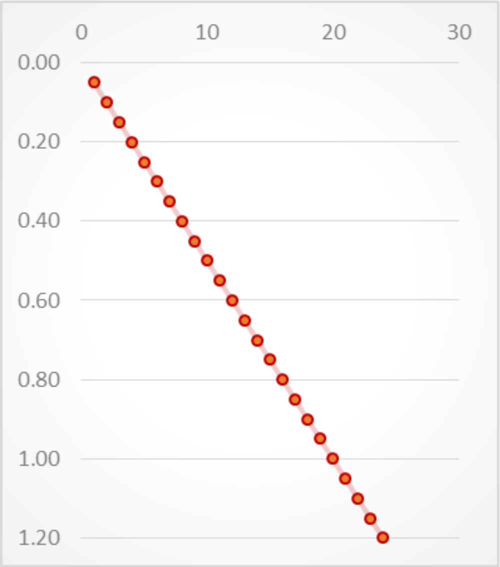
The ASTM standard has some limitations regarding the number and the distribution of the calculation steps in case of Not Uniform calculation.

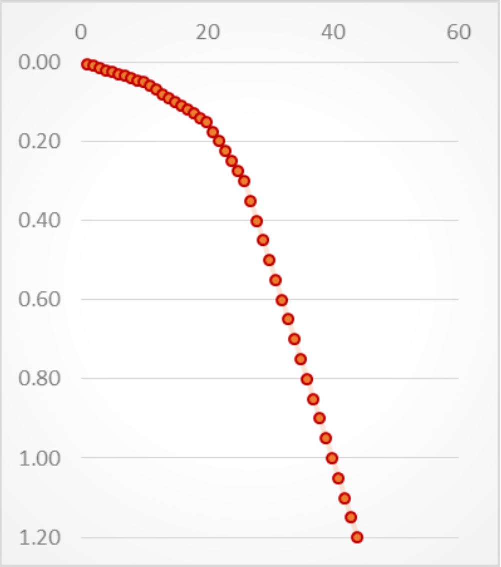
ASTM E837-13: Not Uniform → 20 steps of 0.05mm (for standard strain gage)

**In case residual stresses are expected to have big variations close to the surface, the standard elaboration is not always the best choice.**

Useful hints to overcome this limit:

- Re-calculation of the matrix of coefficient with a depth **accuracy of 10 µm**
- Definition of the **distribution** of the calculation steps (linear, quadratic, cubic or original)



# Hole-Drilling Method – Integral Method

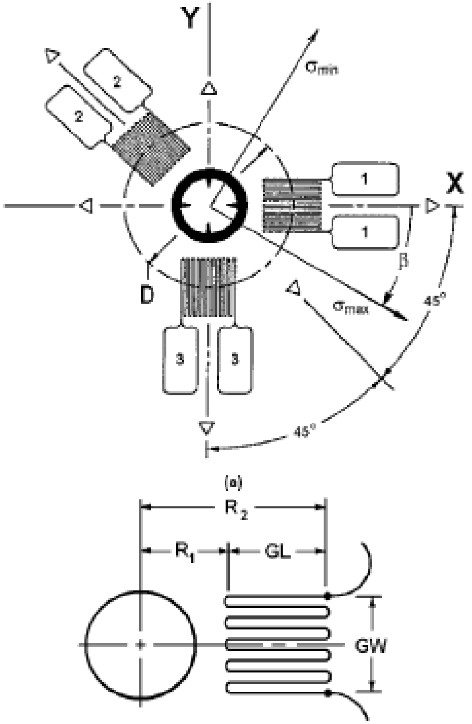
## Integral method

Integral method for residual stress analysis was proposed by G. S. Schajer in 1988 in order to overcome the limits of the old ASTM standard regarding the constant stress field.

Integral method is a numerical method based on **FEM analysis** of hole drilling.

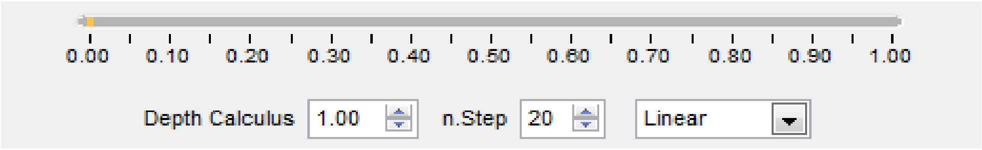
The main parameters of integral model are:

- **$D_0$** Hole diameter
- **$D_{GAGE}$** Strain gage diameter
- **TP** Type of strain gage (for selection of the coefficients calculated by FEM models)
- **z** Number of the drilling steps
- **Z** Number of calculation steps
- **DIS** Distribution of the calculation steps
- **E** Young module
- **v** Poisson ratio



# Integral method

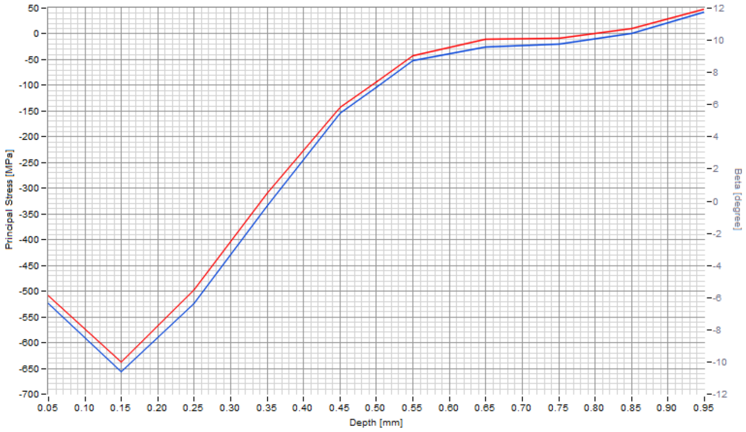
The integral method allows to select the **total depth** of analysis and the **number/distribution** of the steps used in the calculation.



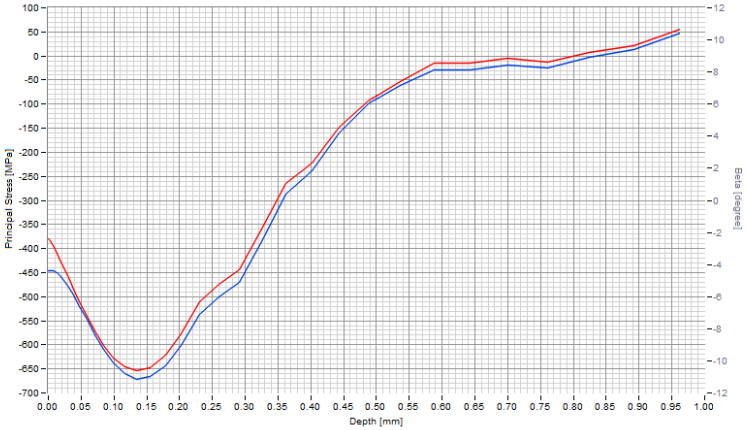

The maximum calculation depth is approximately **$0.2 \cdot D_{GAGE}$** (approx. 1.2mm for standard rosette).

For the large number of steps generally used in the calculation, the matrices of coefficients become **numerically ill-conditioned.**

Without **Tikhonov regularization**, small errors in the measured strains cause proportionally larger errors in the calculated stresses.




Integral method: 10 calculation steps




Integral method: original calculation steps

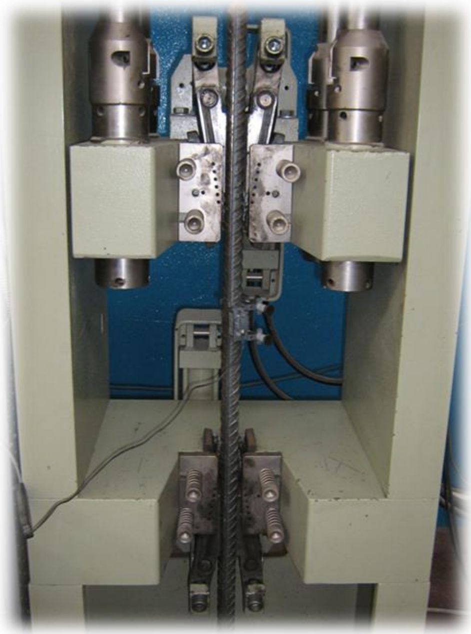
# Schwarz-Kockelmann method

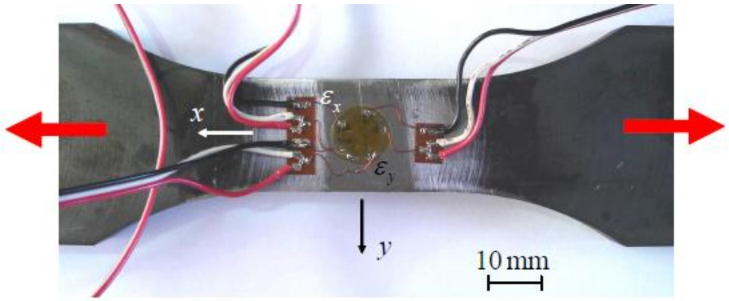
This method, proposed by H. Kockelmann in 1993 is based on the strain ratio measured during the hole drilling.

Schwartz–Kockelmann method is centered on the **experimental/numerical** evaluation of calibration functions $K_x$ and $K_y$. It's valid **only** for HBM strain gage rosette.

The main parameters are the Kockelmann method are:

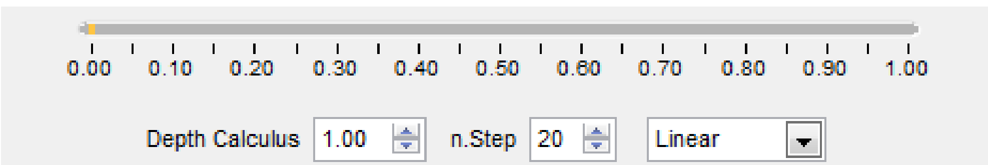
- **$D_0$** Hole diameter
- **$D_{GAGE}$** Strain gage diameter
- **TP** Type of strain gage (for selection of the coefficients calculated by FEM models)
- **z** Number of the drilling steps
- **Z** Number of calculation steps
- **DIS** Distribution of the calculation steps
- **E** Young module
- **v** Poisson ratio





# Schwarz-Kockelmann method

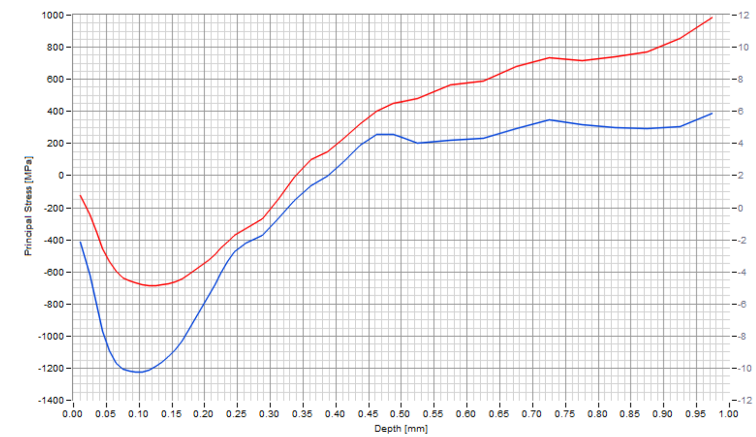
The Schwarz-Kockelmann method allows to select the **total depth** of analysis and the **number/distribution** of the steps used in the calculation.



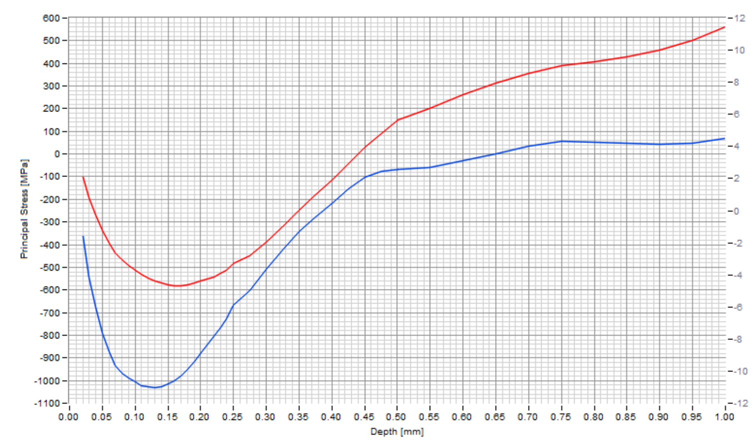

The maximum calculation depth is approximately **$0.2 \cdot D_{GAGE}$** (approx. 1.2mm for standard rosette).

It is a method which has **lower sensitivity** to the effects of experimental errors compared with the Integral method: it assumes that the stress depends only on the depth while integral method considers the contribution of all stresses at all depths simultaneously

**Suggested only for linear or slightly varying stress fields**



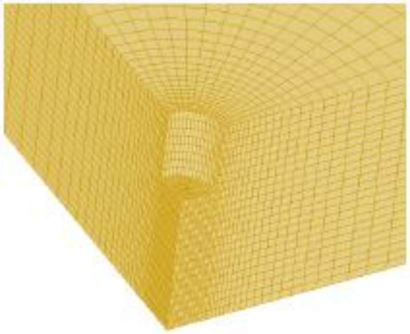

Integral method calculation




Kockelmann method calculation

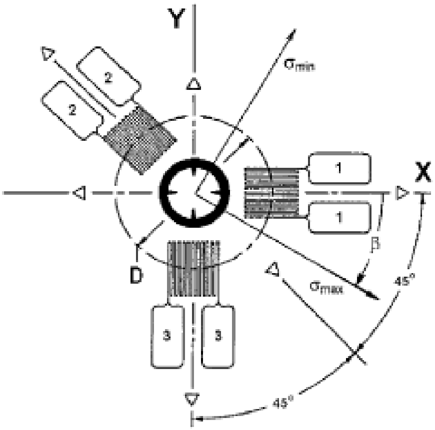
## HDM method

HDM (hole drilling method) is a calculation method for residual stress developed in the 2000s by the University of Pisa.

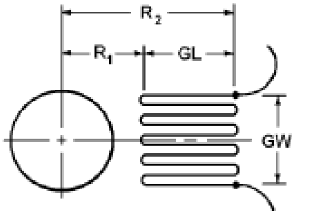


HDM is a numerical method based on **FEM analysis** of hole drilling. The main parameters of HDM model are:

- **$D_0$** Hole diameter
- **$D_{GAGE}$** Strain gage diameter
- **Gw** Grid width
- **GL** Grid length
- **TP** Type of strain gage (for selection of the coefficients calculated by FEM analysis)
- **z** Number of the drilling steps
- **Z** Number of calculation steps
- **DIS** Distribution of the calculation steps
- **E** Young module
- **v** Poisson ratio
- **$e_x$ $e_y$** Eccentricity in x-y direction

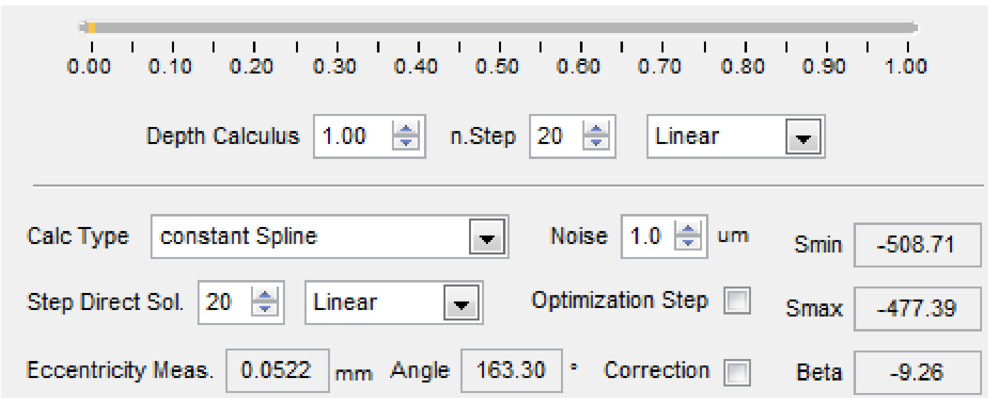



(a)



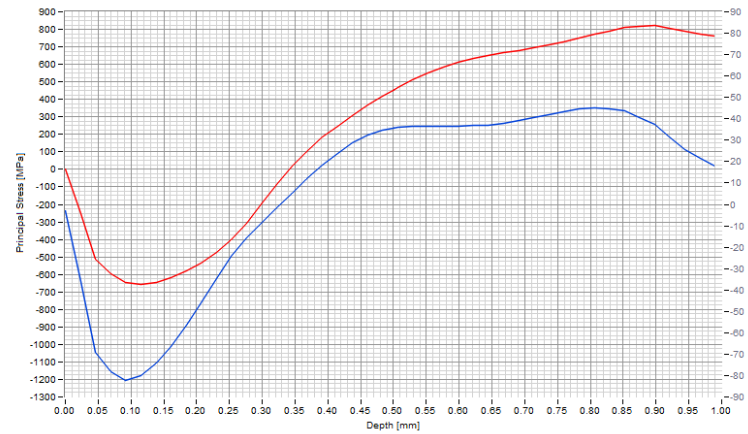
# HDM method

The HDM method allows to select the **total depth** of analysis and the **number/distribution** of the steps used in the calculation. It allows to activate the **Step optimization** and the **Eccentricity correction**.

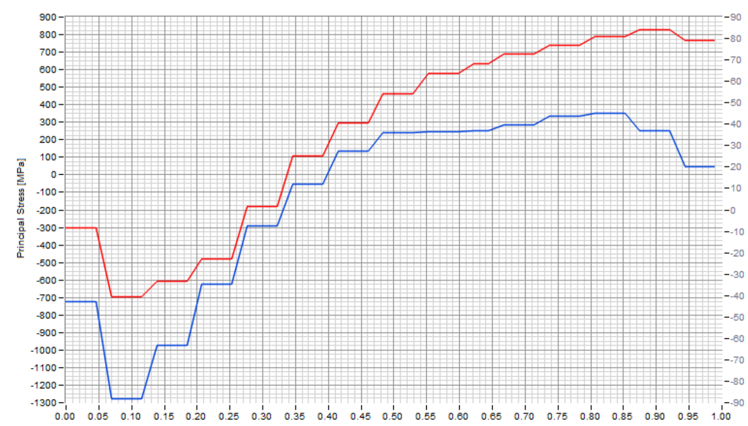



The maximum calculation **depth** is approximately **0.2·$D_{GAGE}$** (approx. 1.2mm for standard rosette).

Using the HDM method the user has a **complete control of the settings**: not only number and steps distribution but also the type of spline curve used for the calculation of stresses (constant, linear, cubic).

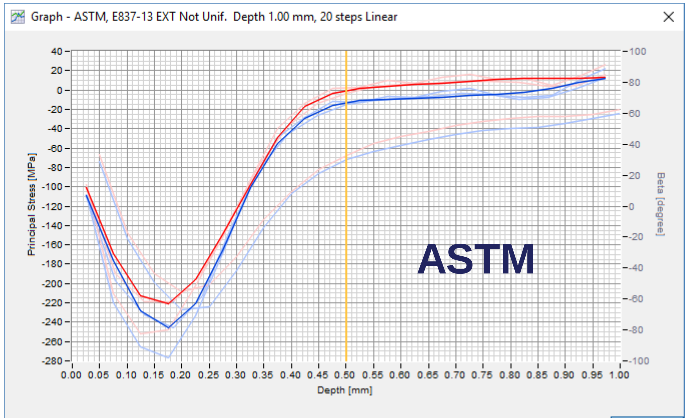



HDM method calculation: linear spline




HDM method calculation: constant spline

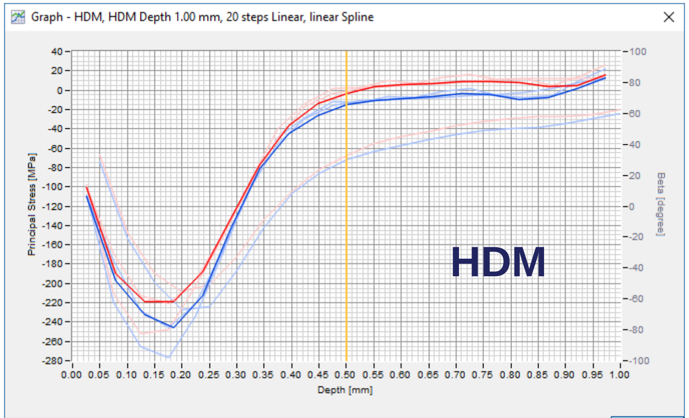
# Comparison between the Different Methods




ASTM, E837-13 EXT Not Unif. Depth 1.00 mm, 20 steps Linear
Tikhonov: ap 2.17E-5, aq 4.83E-5, at 5.24E-5

Depth [mm]: 0.500

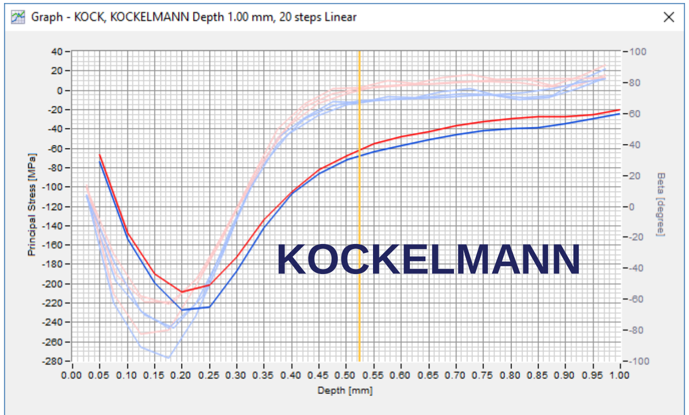
| | S min [MPa] | S max [MPa] | Beta [deg] | e1 [um] | e2 [um] | e3 [um] |
|---|---|---|---|---|---|---|
| ASTM | -13.15 | -0.76 | 79.64 | 229.80 | 241.91 | 238.28 |
| INT | -12.04 | 1.76 | -8.16 | 229.80 | 241.91 | 238.28 |
| KOCK | -71.94 | -67.24 | -73.53 | 229.80 | 241.91 | 238.28 |
| HDM | -14.49 | -3.15 | 82.44 | 229.80 | 241.91 | 238.28 |




HDM, HDM Depth 1.00 mm, 20 steps Linear, linear Spline

Depth [mm]: 0.500

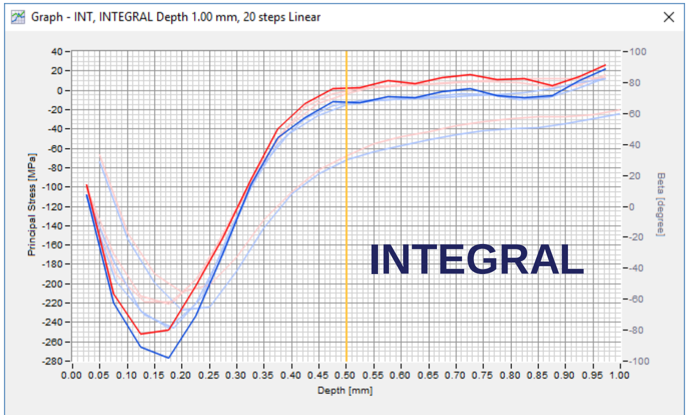
| | S min [MPa] | S max [MPa] | Beta [deg] | e1 [um] | e2 [um] | e3 [um] |
|---|---|---|---|---|---|---|
| ASTM | -13.15 | -0.76 | 79.64 | 229.80 | 241.91 | 238.28 |
| INT | -12.04 | 1.76 | -8.16 | 229.80 | 241.91 | 238.28 |
| KOCK | -71.94 | -67.24 | -73.53 | 229.80 | 241.91 | 238.28 |
| HDM | -14.49 | -3.15 | 82.44 | 229.80 | 241.91 | 238.28 |




KOCK, KOCKELMANN Depth 1.00 mm, 20 steps Linear

Depth [mm]: 0.525

| | S min [MPa] | S max [MPa] | Beta [deg] | e1 [um] | e2 [um] | e3 [um] |
|---|---|---|---|---|---|---|
| ASTM | -10.89 | 1.85 | 86.27 | 234.76 | 246.54 | 242.28 |
| INT | -12.43 | 2.25 | -84.85 | 234.76 | 246.54 | 242.28 |
| KOCK | -67.56 | -61.40 | -77.38 | 234.76 | 246.54 | 242.28 |
| HDM | -12.85 | 0.09 | 3.33 | 234.76 | 246.54 | 242.28 |

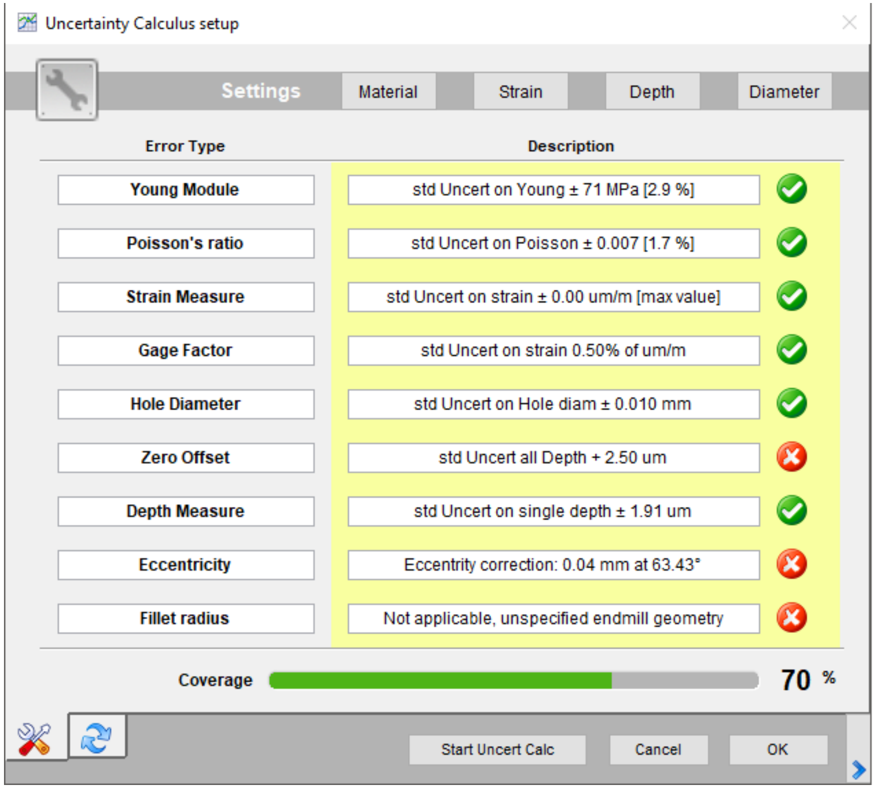



INT, INTEGRAL Depth 1.00 mm, 20 steps Linear

Depth [mm]: 0.500

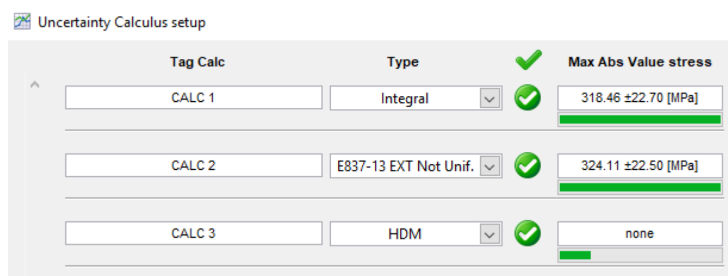
| | S min [MPa] | S max [MPa] | Beta [deg] | e1 [um] | e2 [um] | e3 [um] |
|---|---|---|---|---|---|---|
| ASTM | -13.15 | -0.76 | 79.64 | 229.80 | 241.91 | 238.28 |
| INT | -12.04 | 1.76 | -8.16 | 229.80 | 241.91 | 238.28 |
| KOCK | -71.94 | -67.24 | -73.53 | 229.80 | 241.91 | 238.28 |
| HDM | -14.49 | -3.15 | 82.44 | 229.80 | 241.91 | 238.28 |

# Typical Measurement Uncertainty

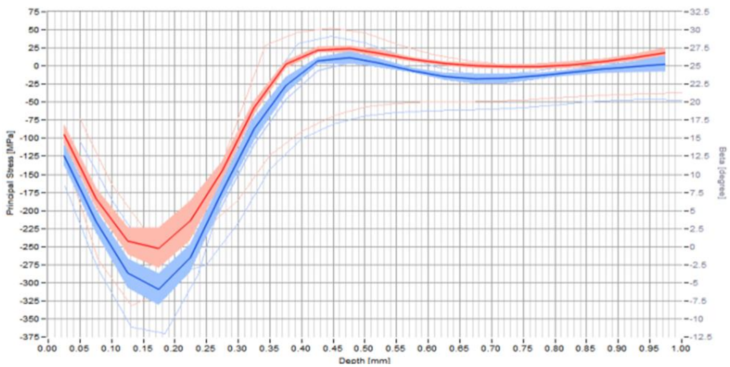


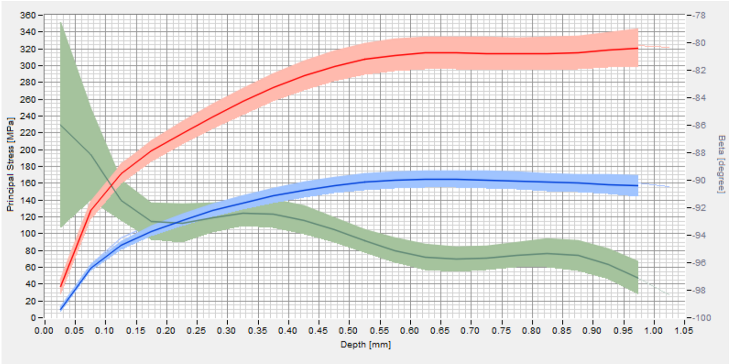

Setup of the **main sources of uncertainty**:

Calculation setup:




Typical test results:

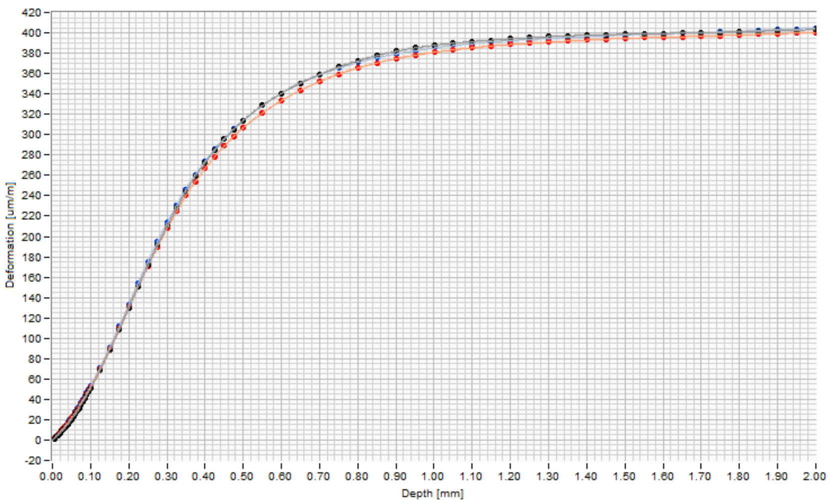


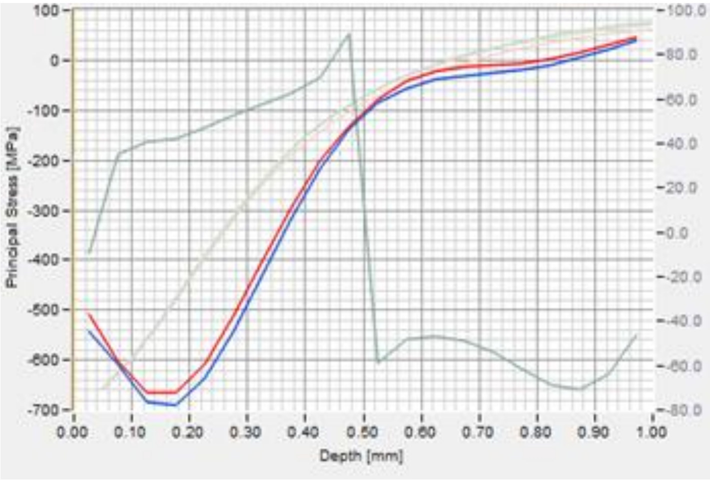
# Typical Test Results – HD Method

TEST DESCRIPTION

- **Shot peened surface**
- Acquisition of rosette strains
- Processing of results
- **Calculation** of residual stress in accordance with ASTM standard




Acquisition of rosette strains

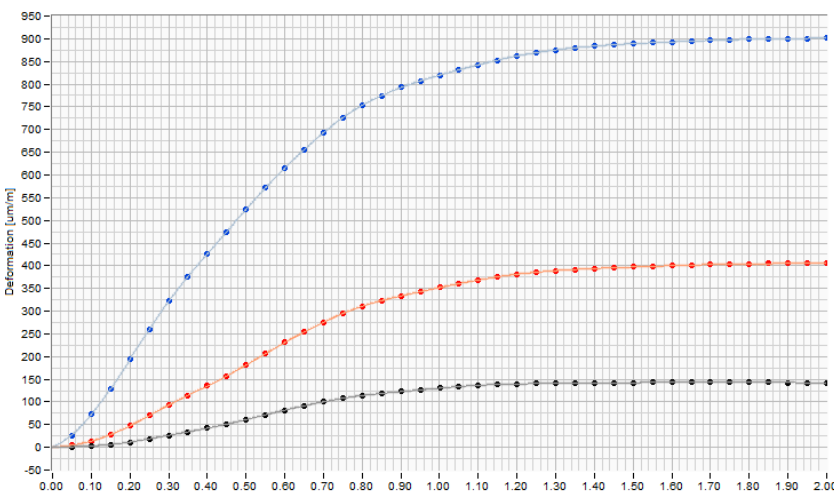



Pattern of residual stress

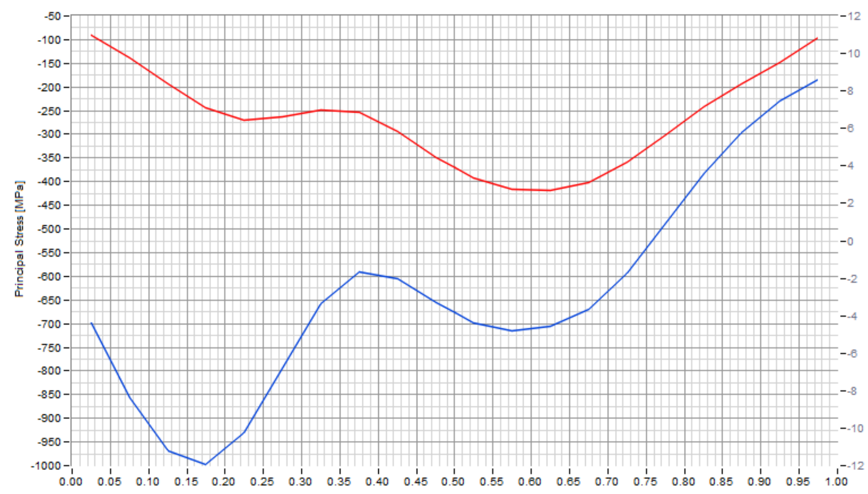
# Typical Test Results – HD Method

TEST DESCRIPTION

- **Oil-quenched surface**
- Acquisition of rosette strains
- Processing of results
- **Calculation** of residual stress in accordance with ASTM standard

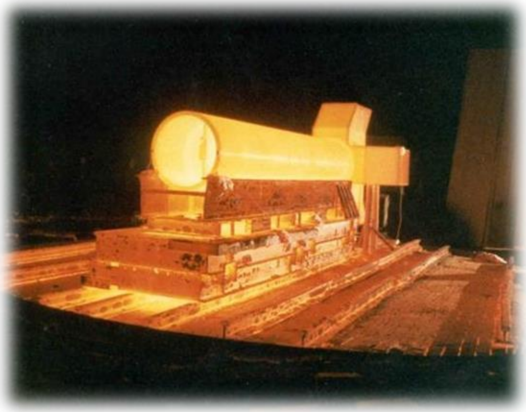



Acquisition of rosette strains



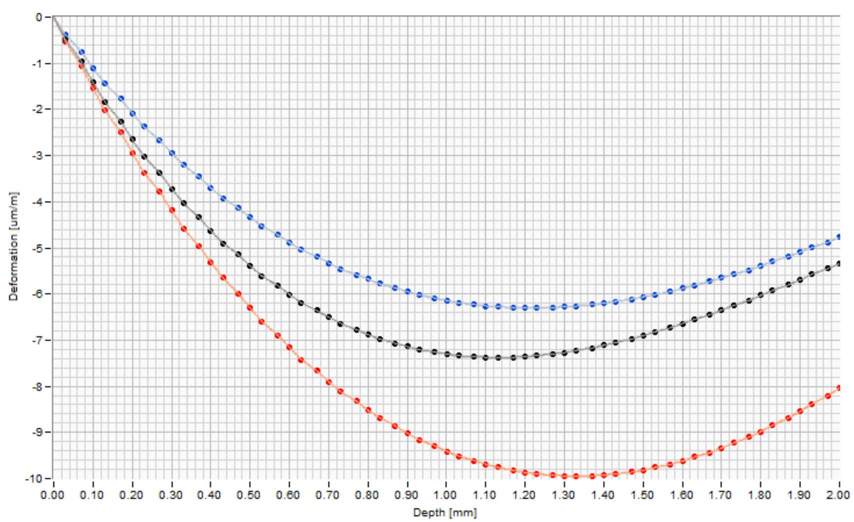

Pattern of residual stress

# Typical Test Results – HD Method

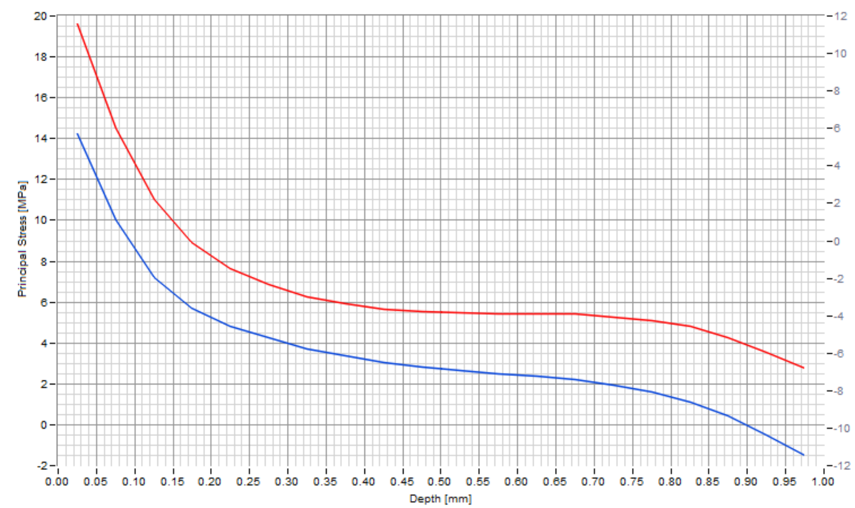


<u>TEST DESCRIPTION</u>

- **Stress-relieved surface**
- Acquisition of rosette strains
- Processing of results
- **Calculation** of residual stress in accordance with ASTM standard

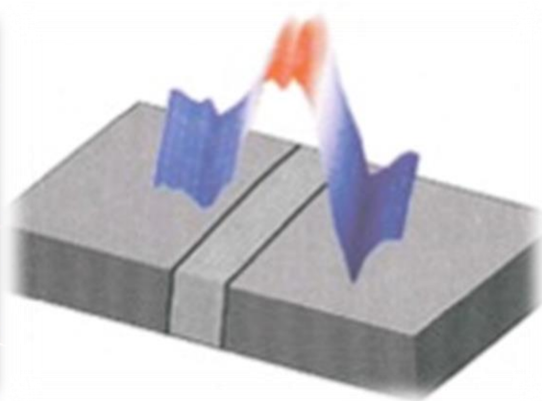



Acquisition of rosette strains



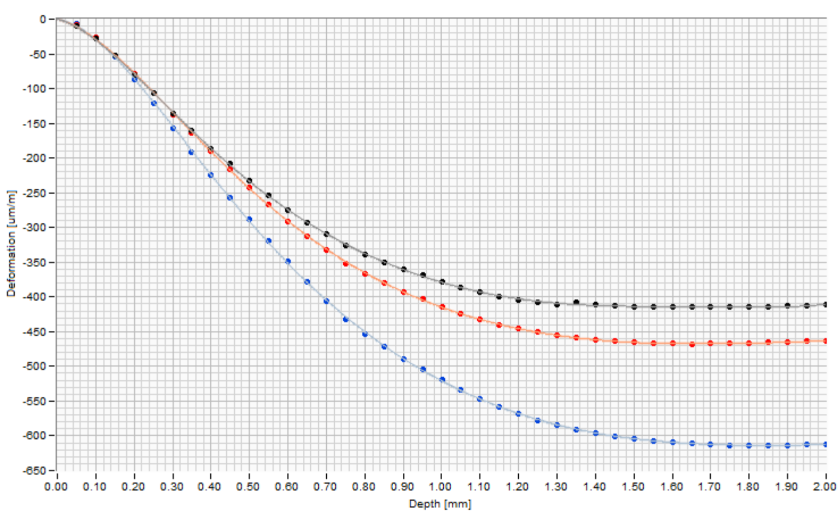

Pattern of residual stress

# Typical Test Results – HD Method

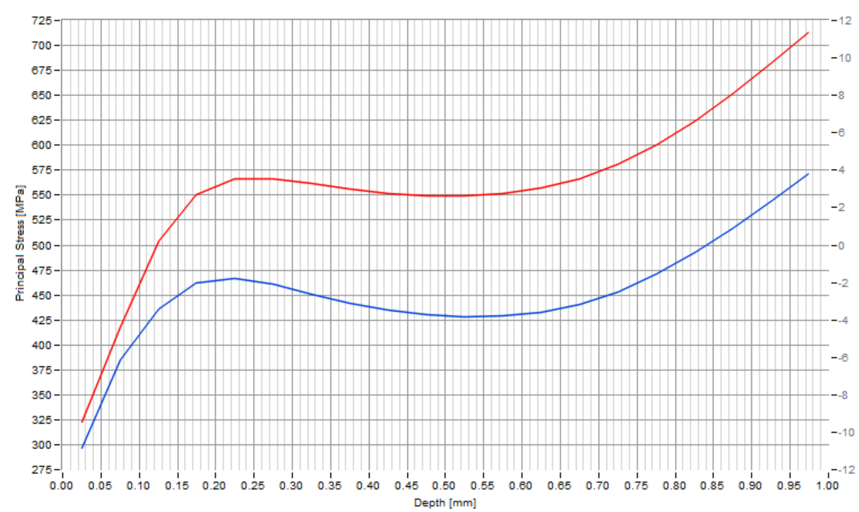


TEST DESCRIPTION

- **Welded surface (HAZ area)**
- Acquisition of rosette strains
- Processing of results
- **Calculation** of residual stress in accordance with ASTM standard



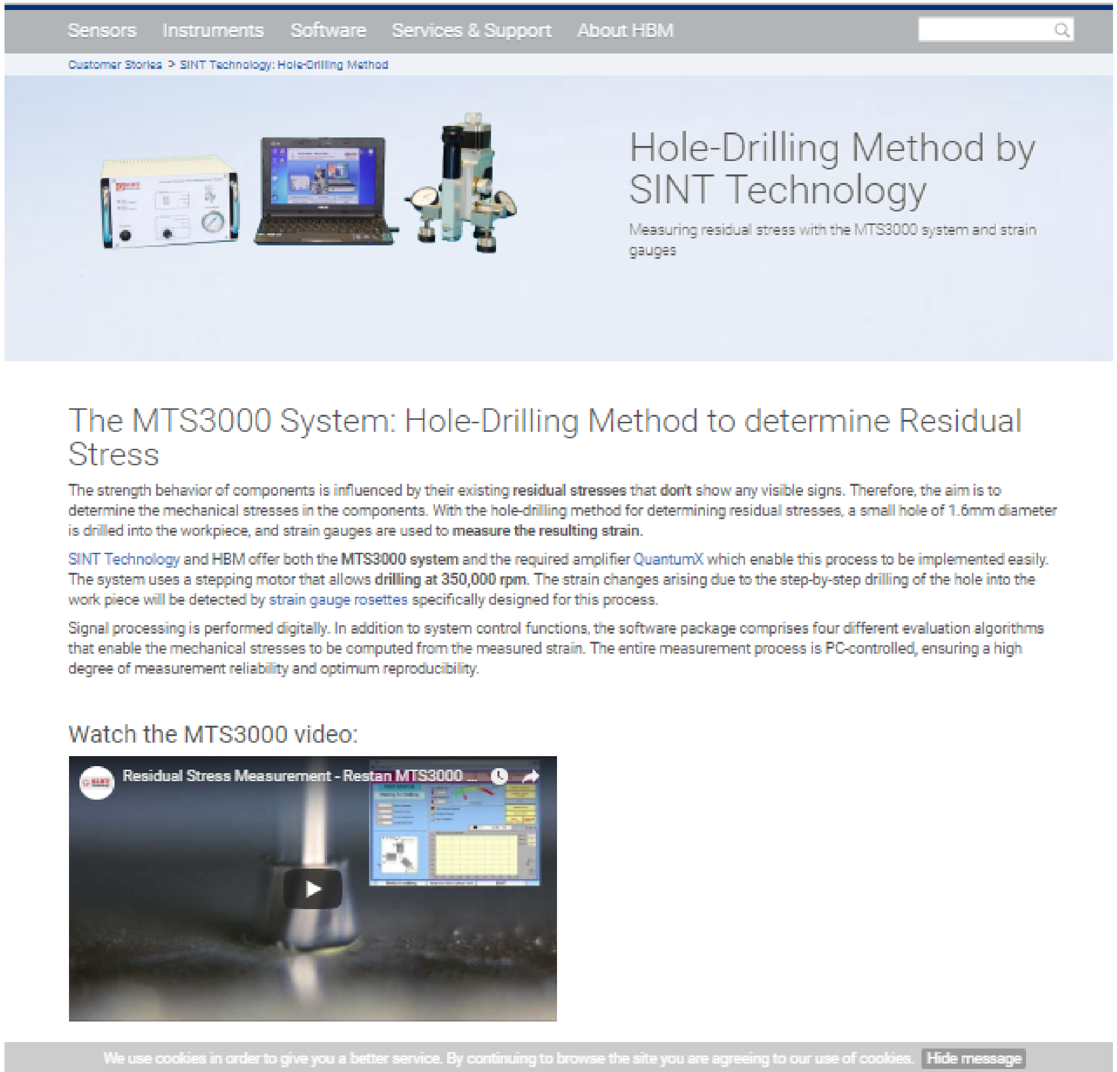

Acquisition of rosette strains




Pattern of residual stress

# More Detailed Information

- [www.hbm.com/sint](http://www.hbm.com/sint)



Sensors Instruments Software Services & Support About HBM

Customer Stories > SINT Technology: Hole-Drilling Method

Hole-Drilling Method by SINT Technology

Measuring residual stress with the MTS3000 system and strain gauges

The MTS3000 System: Hole-Drilling Method to determine Residual Stress

The strength behavior of components is influenced by their existing **residual stresses** that **don't** show any visible signs. Therefore, the aim is to determine the mechanical stresses in the components. With the hole-drilling method for determining residual stresses, a small hole of 1.6mm diameter is drilled into the workpiece, and strain gauges are used to **measure the resulting strain.**

SINT Technology and HBM offer both the **MTS3000 system** and the required amplifier QuantumX which enable this process to be implemented easily. The system uses a stepping motor that allows **drilling at 350,000 rpm**. The strain changes arising due to the step-by-step drilling of the hole into the work piece will be detected by strain gauge rosettes specifically designed for this process.

Signal processing is performed digitally. In addition to system control functions, the software package comprises four different evaluation algorithms that enable the mechanical stresses to be computed from the measured strain. The entire measurement process is PC-controlled, ensuring a high degree of measurement reliability and optimum reproducibility.

Watch the MTS3000 video:

Residual Stress Measurement - Restan MTS3000 ...

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