RECENT ADVANCEMENTS IN THE HOLE-DRILLING STRAIN-GAUGE RESIDUAL STRESS METHOD

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Summary

- Who is SINT Technology
- Nature and source of residual stresses
- General background on calculation methods
- Hole-drilling strain-gage method
- Typical measurement results on metals
- Measuring residual stress in polymers: main issues
- Important hints to improve the technique
- General background on measurement uncertainty
- Main sources of uncertainty of the hole-drilling method
- How to take into account the different contributions
- Examples and typical test results
- Q&A

Who is SINT Technology – General info

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

SINT Technology has **45 employees**. Most of them are engineers with average age of about 35 years.

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

ilac-MRA

ACCREDIA
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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

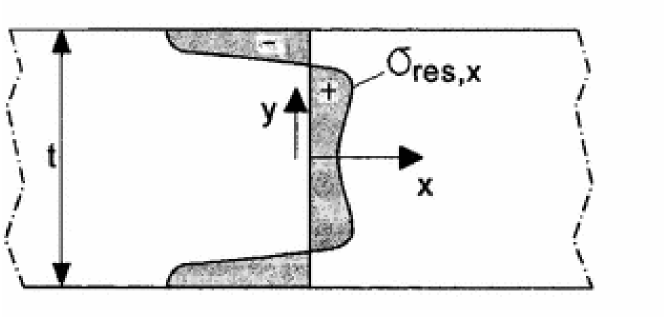
Software solutions

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

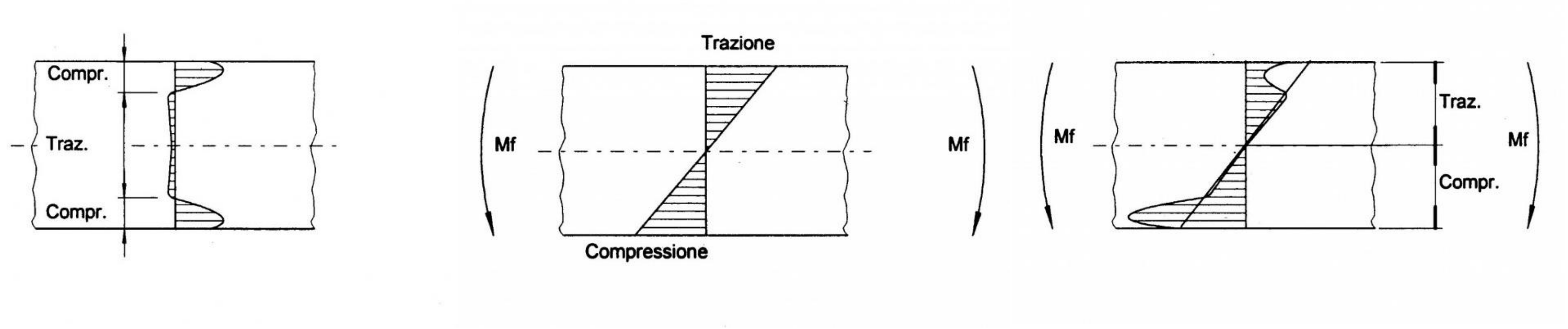
$$\int_{-t/2}^{t/2} y \cdot \sigma_x \cdot dy = 0$$

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:

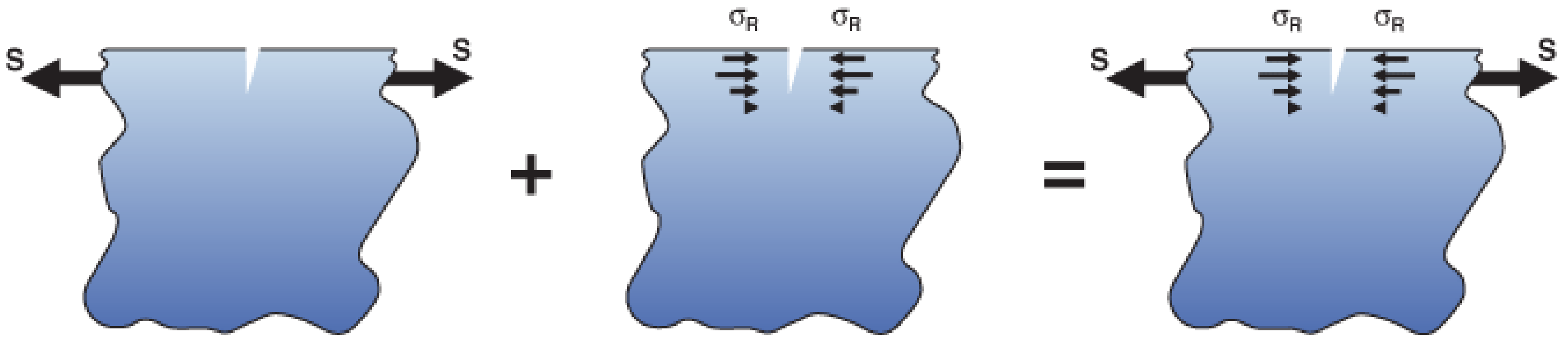
$$\sigma_{TOTAL} = \sigma_{RS} + \sigma_{EXT}$$



Residual Stress (e.g. Shot Peening)

External Load (e.g. Bending)

Total Load



General Background on Calculation Methods

Residual stress measurement methods are typically divided into three general types:

✓ **Mechanical Relaxation Methods**

These are the **most generally applicable** methods for a wide range of materials, both metallic and non-metallic.

They involve measuring the **deformations** caused by the cutting of some part of the stressed specimen. The resulting specimen damage can sometimes be quite extensive, but often is minimal and unharmful.

✓ **Diffractive Methods**

These include X-ray, Synchrotron and Neutron Diffraction methods.

These methods have the advantage of being **non-destructive**, but are limited to **crystalline** materials. The X-ray technique can measure only **very near-surface** stresses.

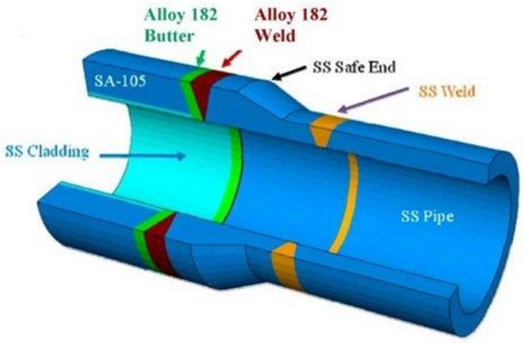
✓ **Other Methods**

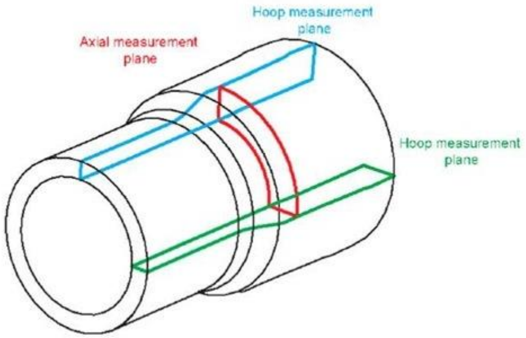
These include magnetic, ultrasonic, thermo-elastic and photoelastic methods.

These are more specialized measurement methods suited to **particular materials**, based on specific properties of those materials and requiring detailed material-specific **calibrations**.

General Background on Calculation Methods

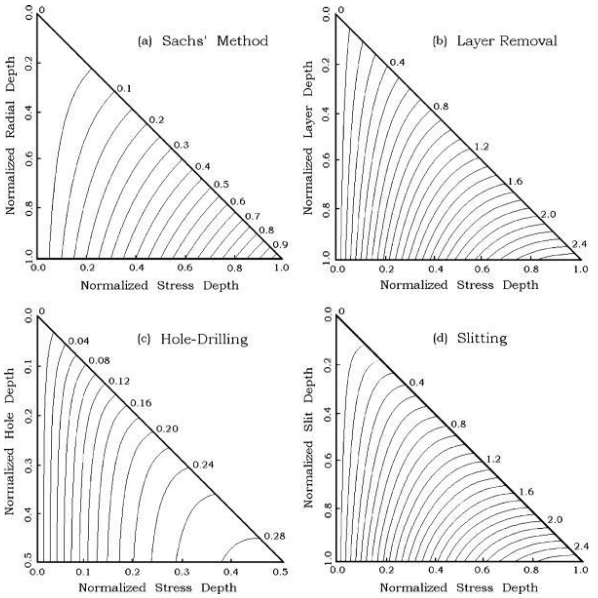
The **mechanical relaxation methods** for measuring residual stresses generally use **strain gages** to measure the **deformation change** that occurs in the given specimen.





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.

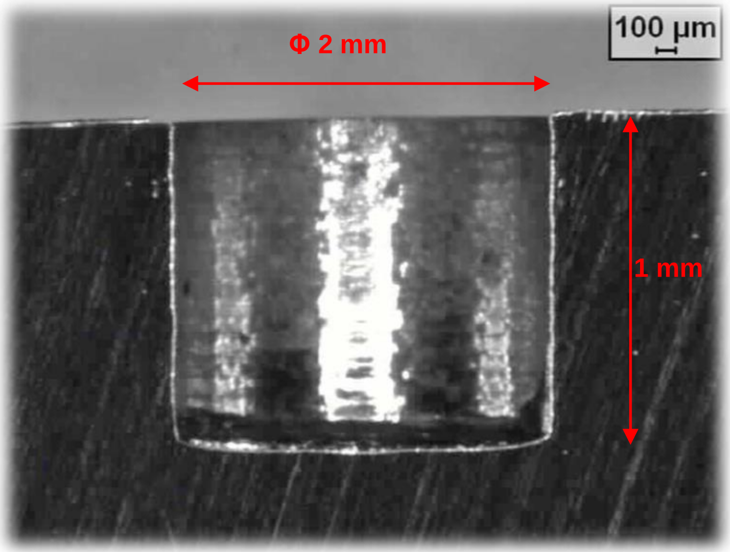
The **deformations** associated with this stress redistribution provide the data from which to **evaluate** the originally existing residual stresses. Since the material cutting locally reduces the original residual stresses, the various procedures used are called “relaxation” methods.

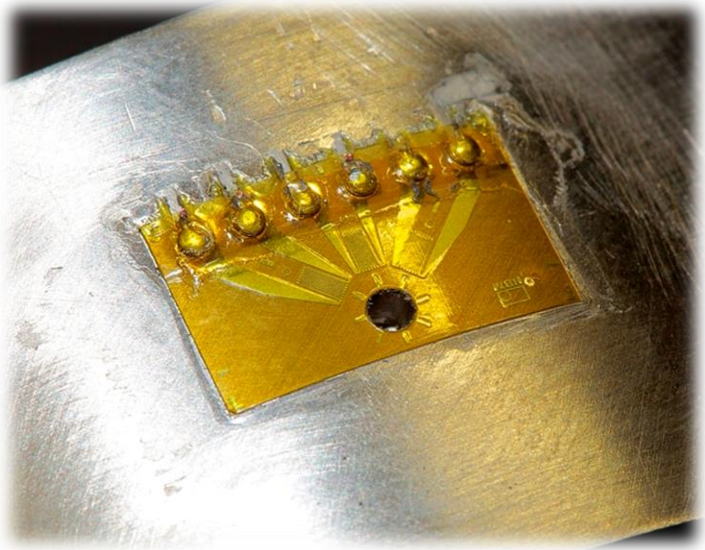


Hole-Drilling Strain-Gage Method

The hole drilling method consists in drilling a small hole (**approx. 2 mm diameter x 1 mm depth**, up to 4 mm diameter x 2 mm depth) into the center of a special SG rosette.

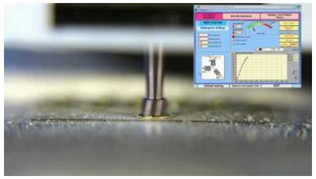
The hole locally releases the strains, allowing redistribution of the residual stresses originally existing in the material.





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).

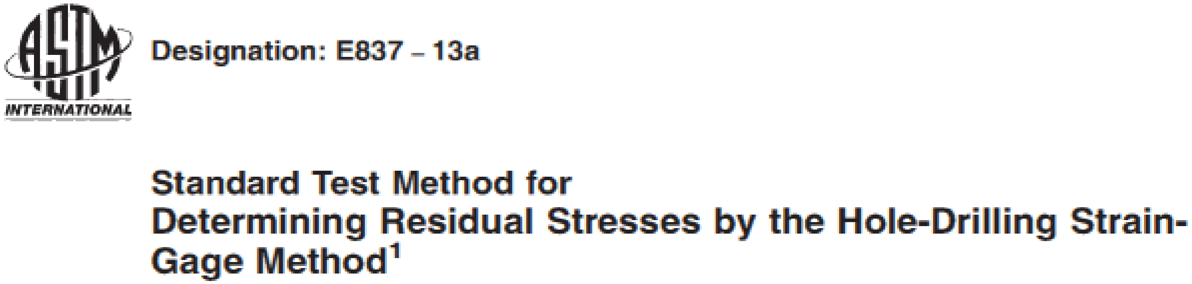
VIDEO



Hole-Drilling Strain-Gage Method

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.



Designation: E837 – 13a

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

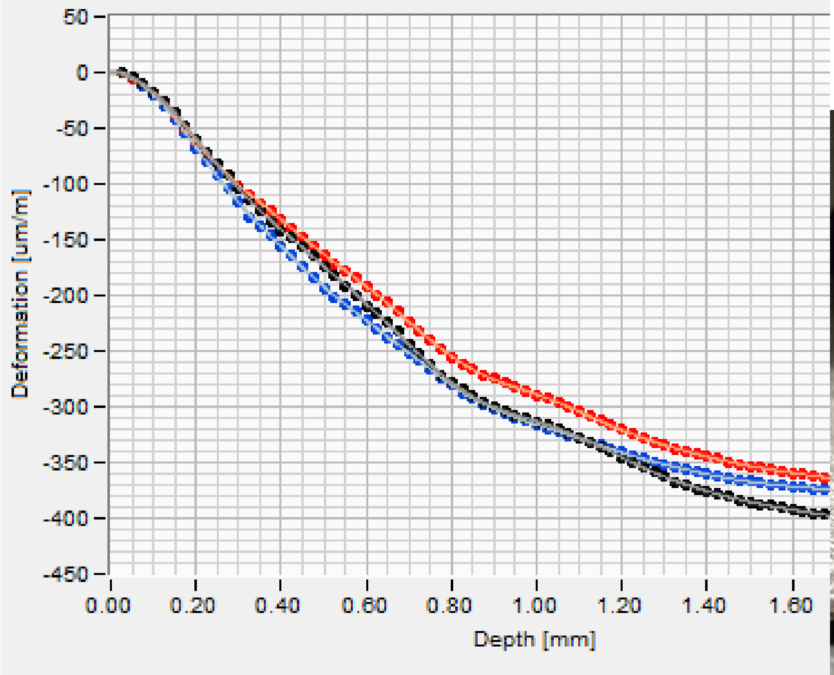
Standard ASTM E837-13 describes:

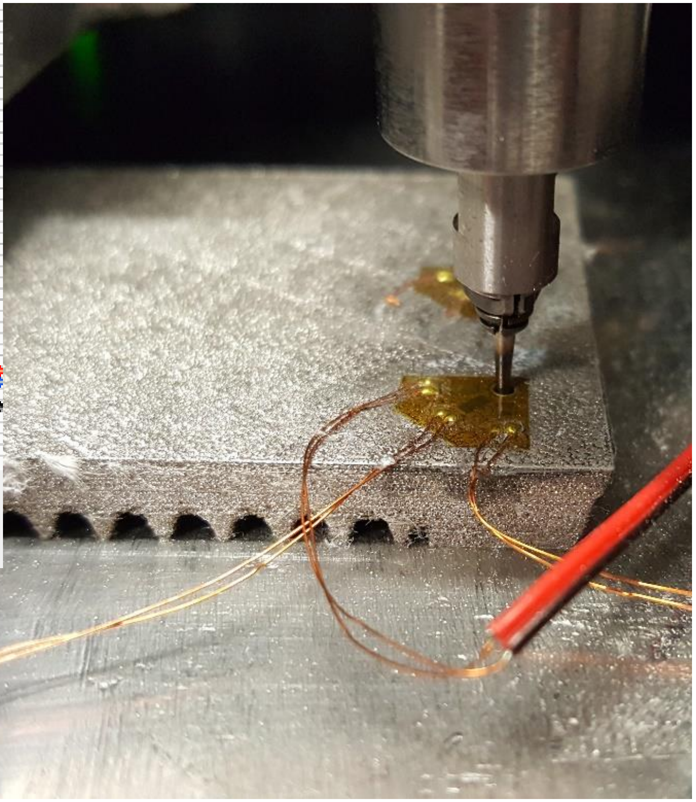
- Established **experimental** and **analytical** procedures for **reliable** residual stress evaluations
- **Limit of applicability** of the method
- The total drilling / analysis **depth** and the applicable **calculation algorithms**
- The number of **drilling increments** required
- The **numerical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

Typical Measurement Results on Metals

NEW PRODUCTION TECHNIQUE - ADDITIVE MANUFACTURING - STRAIN

(Production of 3D objects by adding layer-upon-layer of material)

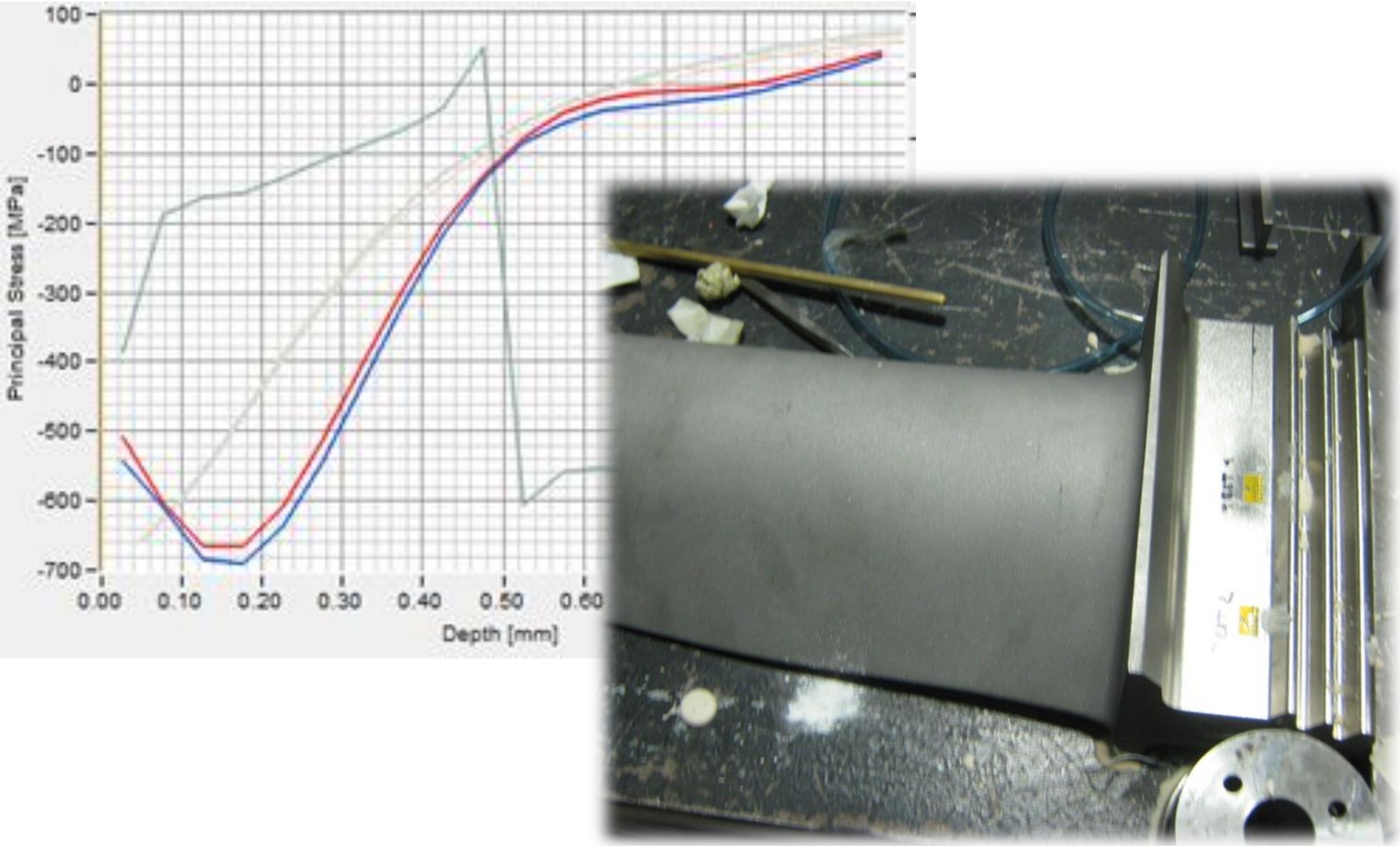




Typical Measurement Results on Metals

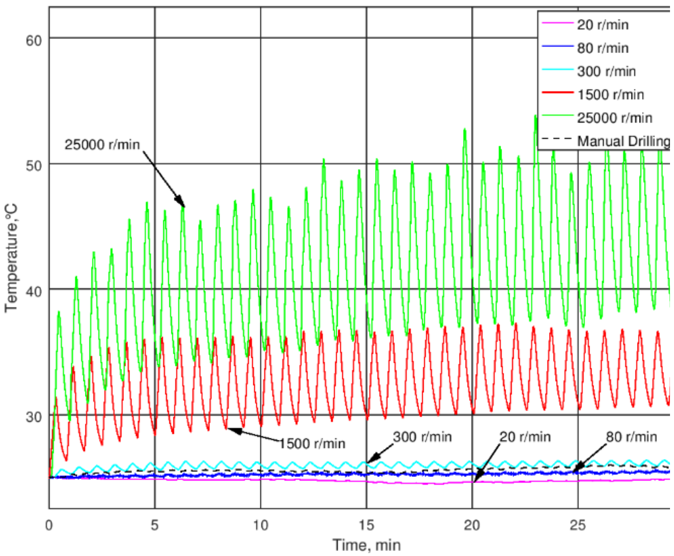
OIL & GAS INDUSTRY – SHOT PEENING PROCESS - ***STRESS***

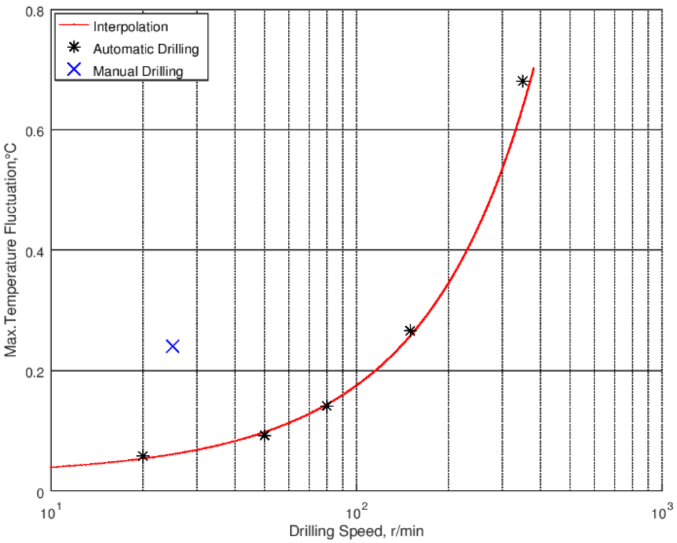
(compressor and turbine parts)

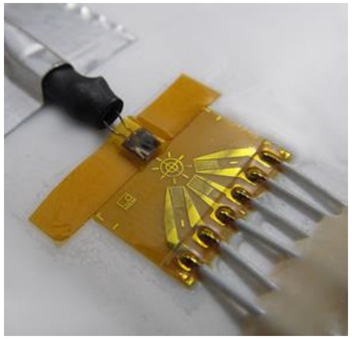


Measuring Residual Stress in Polymers: Main Issues

When drilling **polymeric materials**, the **drilling speed** must be much **lower** if compared with metals, in order to avoid **thermal and mechanical effects** on the material or even melting during the drilling process. The rotational speeds of 20, 50, 80, 150, 300, 1500 and 25000 r/min and manual drilling (approx. 25 r/min), were investigated during automatic drilling tests (feed rate 0.2mm/min) and surface temperature variation was measured.







20 and 50 r/min
$\Delta T \leq 0.1°C$

Automatic 20 r/min rotational speed generates a lower temperature variation on the surface

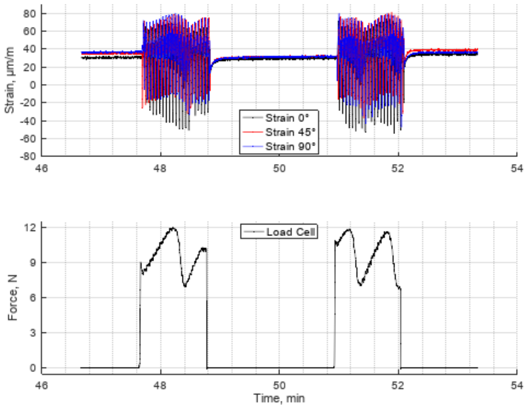
Valentini, E., Bertelli, L., and Benincasa, A., "Improvements in the Hole-Drilling Test Method for Determining Residual Stresses in Polymeric Materials," Materials Performance and Characterization", https://doi.org/10.1520/MPC20170123. ISSN 2379-1365.

Measuring Residual Stress in Polymers: Main Issues

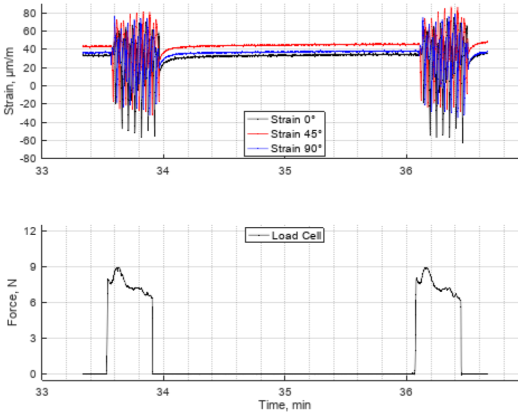
Tests at **20 RPM** and different feed rates. Measurement of **strains and axial force**

Low FEED RATES → Increase **friction** in the area of contact of the end mill → **Higher temperature** fluctuation **Higher axial force** generated

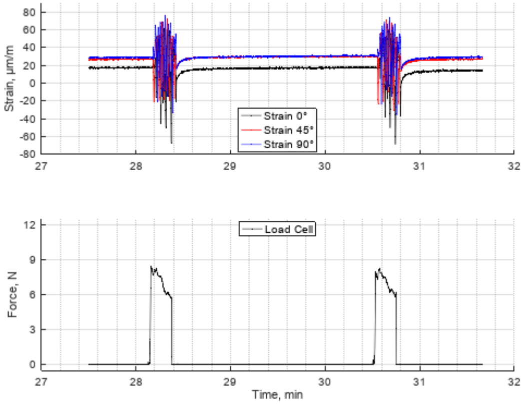
0.05 mm/min



0.20 mm/min



0.50 mm/min



Feed rate of **0.2 – 0.5 mm/min** minimizes the axial force exerted and the **temperature variation**

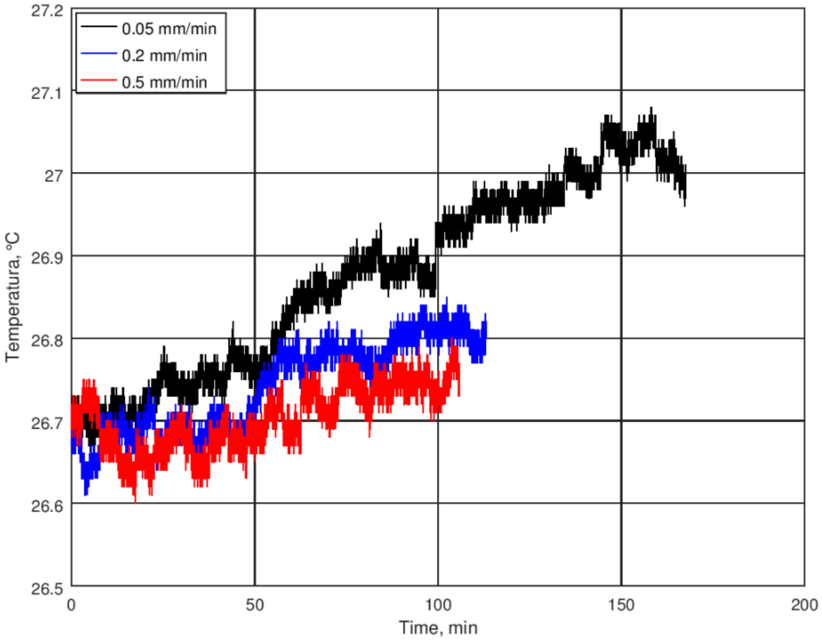
Measuring Residual Stress in Polymers: Main Issues

Tests at **20 RPM** and different feed rates. Measurement of **surface temperature** near the gauges

Low FEED RATES

Increase **friction** in the area of contact of the end mill

Higher temperature fluctuation
Higher axial force generated



Low feed rates cause larger temperature fluctuations and higher temperature increase during drilling.

This is probably caused by higher frictional losses because of the low feed per revolution.

Important Hints to Improve the Technique

PROBLEM

High Thermal Expansion Thermal Compensation difficult to achieve

Low Thermal Diffusivity of the material

Viscoelastic behavior of the material

SOLUTION

Dummy Gage configuration

S.G. rosette compensated for **Aluminum alloy**

Temperature controlled environment with minimum temperature fluctuations

Low Supply Voltage (0.5V) of the strain gage bridge

Minimization of the **local heating** generated by the drilling process

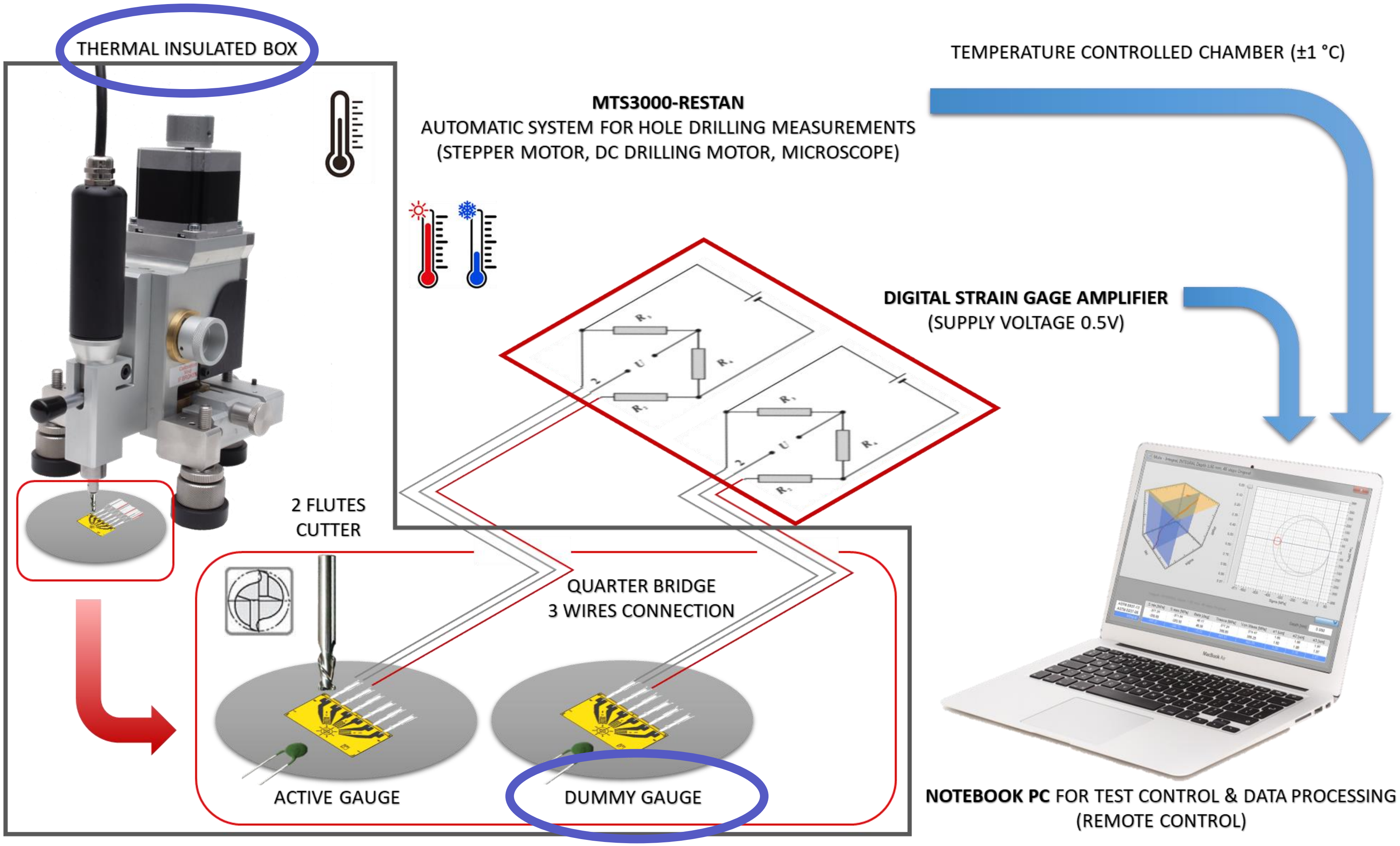
Suitable **stabilization time** before the strain measurement

Minimization of the **local forces** generated by the drilling process

Suitable **stabilization time** before the strain acquisition

The **Automatic Drilling System** with **Remote Control** helps for the minimization of the **local heating** and **local forces** (controlled drilling process) and avoids **fluctuations of the ambient temperature** (operator is far from the drilling tool)

Important Hints to Improve the Technique



THERMAL INSULATED BOX

TEMPERATURE CONTROLLED CHAMBER (±1 °C)

MTS3000-RESTAN
AUTOMATIC SYSTEM FOR HOLE DRILLING MEASUREMENTS
(STEPPER MOTOR, DC DRILLING MOTOR, MICROSCOPE)

DIGITAL STRAIN GAGE AMPLIFIER
(SUPPLY VOLTAGE 0.5V)

2 FLUTES
CUTTER

QUARTER BRIDGE
3 WIRES CONNECTION

ACTIVE GAUGE

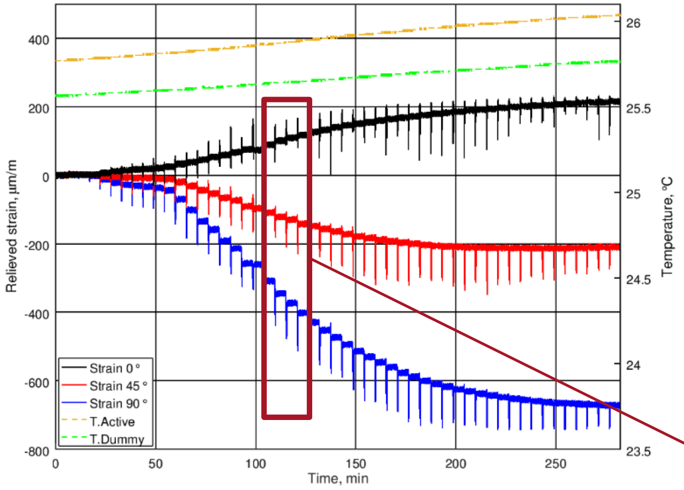
DUMMY GAUGE

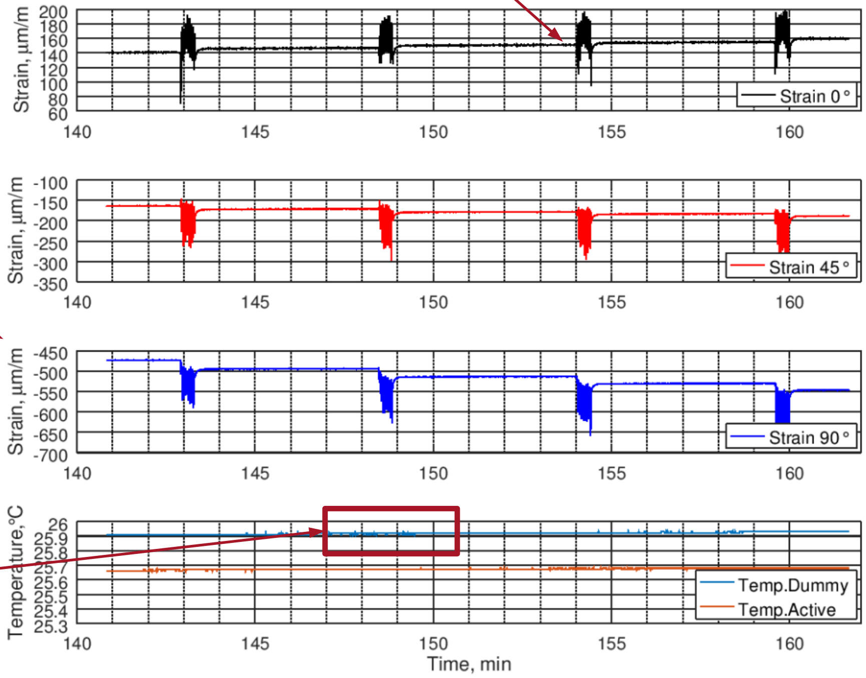
NOTEBOOK PC FOR TEST CONTROL & DATA PROCESSING
(REMOTE CONTROL)

Important Hints to Improve the Technique

Typical trend of the correct strain reading vs. time during the complete hole drilling process: strain alterations are generated by the drilling process

Acquisition is done **after the stabilization** time of the strains signals.





The temperature variation due to the effect of the drilling process is **negligible**.

General Background on Measurement Uncertainty

It is important not to confuse the terms **error** and **uncertainty**.

Error is the difference between the measured value and the ‘true value’ of the thing being measured.

Uncertainty is a quantification of the doubt about the measurement result.

The effects that give rise to uncertainty in measurement can be either:

- **random** - where repeating the measurement gives a randomly different result. If so, the more measurements you make, and then average, the better estimate you generally can expect to get.
- **systematic** - where the same influence affects the result for each of the repeated measurements (but you may not be able to tell). In this case, you learn nothing extra just by repeating measurements. Other methods are needed to estimate uncertainties due to systematic effects, e.g. different measurements, or calculations.

General Background on Measurement Uncertainty

The case of interest is where the quantity Y being measured, called the **measurand**, is not measured directly, but is determined from N other quantities $X_1, X_2, \ldots, X_N$ through a functional relation f, often called the **measurement equation**:

$$Y = f(X_1, X_2, \ldots., X_N,)$$

An estimate of the measurand or output quantity Y, denoted by y, is obtained from measurement equation using input estimates $x_1, x_2, \ldots, x_N$ for the values of the N input quantities $X_1, X_2, \ldots, X_N$.

Thus, the **output estimate** y, which is the **result of the measurement**, is given by:

$$y = f(x_1, x_2, \ldots., x_N,)$$

The **uncertainty** of the measurement result y arises from the uncertainties $u(x_i)$ (or u_i for brevity) of the input estimates x_i that enter in equation used for an estimate of the quantity y.

General Background on Measurement Uncertainty

The **combined standard uncertainty** of the measurement result *y*, designated by $u_c(y)$ and taken to represent the estimated standard deviation of the result, is obtained from:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} \left[\frac{\partial f}{\partial x_i}\right]^2 \cdot u^2(x_i)}$$

- Equation is generally referred to as **law of propagation of uncertainty**
- The partial derivatives of *f* with respect to the X_i (often referred to as **sensitivity coefficients**) are equal to the partial derivatives of f with respect to the X_i evaluated at $X_i = x_i$
- $u(x_i)$ is the standard uncertainty associated with the input estimate x_i

The equation of the law of propagation of uncertainty is strictly valid under the hypothesis that the **input quantities** X_i can be assumed to be **uncorrelated**.

General Background on Measurement Uncertainty

The **combined standard uncertainty** u_c is used to express the uncertainty of many measurement results. However, for several commercial, industrial, and regulatory applications what is often required is a measure of uncertainty that defines an interval about the measurement result y within which the value of the measurand Y can be confidently asserted to lie.

The measure of uncertainty intended to meet this requirement is termed **expanded uncertainty**, suggested symbol U, and is obtained by multiplying $u_c(y)$ by a **coverage factor**, suggested symbol k.

$$U(y) = k \cdot u_c(y)$$

Usually, the value of the coverage factor k is chosen on the basis of the desired **level of confidence** to be associated with the interval defined by $U = ku_c$.

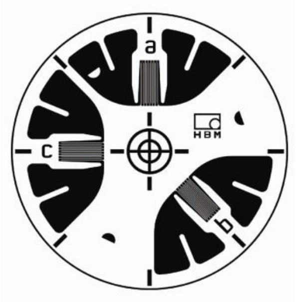
In general the value of the measurand Y can be indicated as:

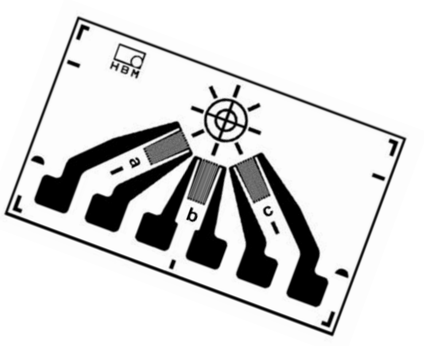
$$\mathrm{Y} = y \pm U(y)$$

Main Sources of Uncertainty of the Hole-Drilling Method

The **main** sources of uncertainty that affect the strain reading are the following:

- Uncertainty connected with the **strain values** (*U_Strain*),
  - ✓ Uncertainty connected with the declaration of the Gage Factors of each grid of the strain gage rosette (*U_k)*
  - ✓ Class of precision of the strain gage amplifier used for the acquisition of the strain values (*U_Class)*
  - ✓ Linearity error (% of Full Scale) of the strain gage amplifier used for the acquisition of the strain values (*U_Linearity*)
  - ✓ Repeatability (µm/m) on the strain gage measurement (*U_Noise)*





Main Sources of Uncertainty of the Hole-Drilling Method

The **main** sources of uncertainty that affect the material properties are the following:

- Uncertainty connected with definition of the **Young module** of the testing material *(U_Young*),
- Uncertainty connected with definition of the **Poisson's ratio** of the testing material *(U_Poisson*),

The **main** sources of uncertainty that affect the diameter of the drilled hole are the following:

- Uncertainty connected with the measure of the **diameter of the drilled hole** (*U_Diameter*),
  - ✓ Minimum resolution of the dial gauge used for the measure of the drilled hole (*U_Res_Dial)*
  - ✓ Accuracy of the dial gauge used for the measure of the drilled hole (*U_Acc_Dial)*
  - ✓ Hysteresis error of the dial gauge used for the measure of the drilled hole (*U_Hyst_Dial*)
  - ✓ Repeatability error of the dial gauge used for the measure of the drilled hole (*U_Rep_Dial*)

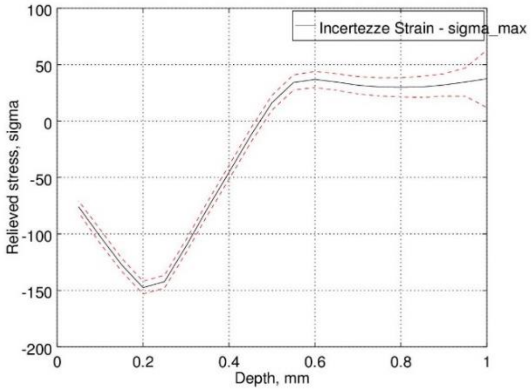
Main Sources of Uncertainty of the Hole-Drilling Method

The **main** sources of uncertainty that affect the hole depth are the following:

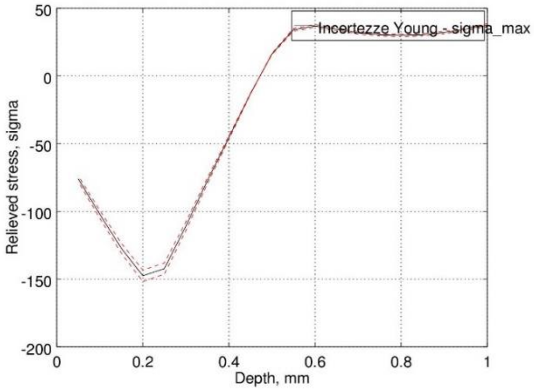
- Uncertainty connected with **depth of the drilled hole** (*U_Depth*),
    - ✓ Minimum resolution of the MTS3000 system in the depth increments (*U_Res_MTS)*
    - ✓ Accuracy of the MTS3000 system in 2 consecutive depth increments (*U_Acc_MTS)*
    - ✓ Repeatability error of the MTS3000 system in the depth increments (*U_Rep_MTS*)

- Uncertainty connected with the determination of the zero depth (**Zero Setting**) (*U_Zero*)

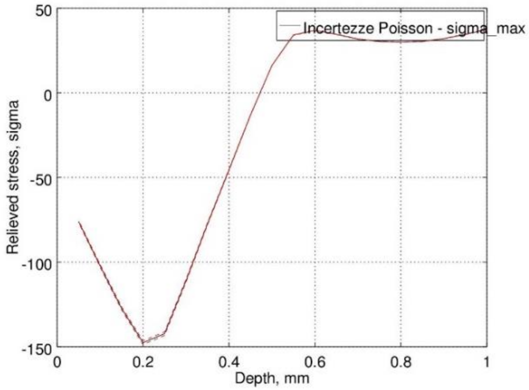
How to Take into Account the Different Contributions



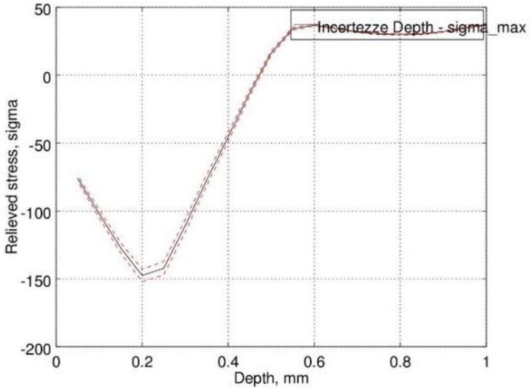
Strain Gage



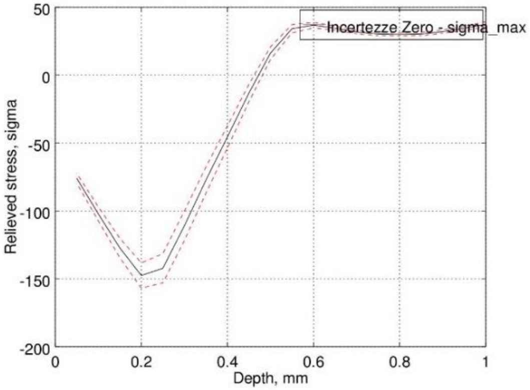
Young Module



Poisson’s Ratio

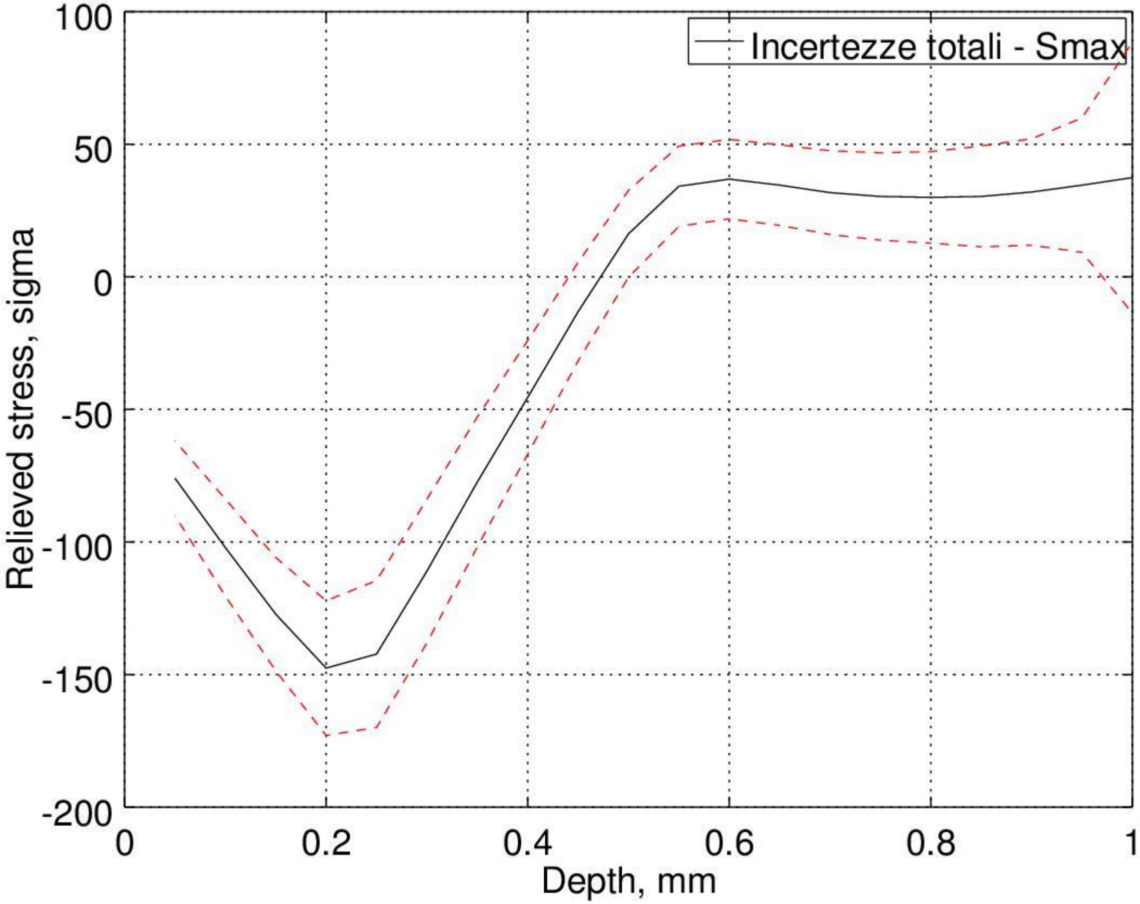


Depth Increments



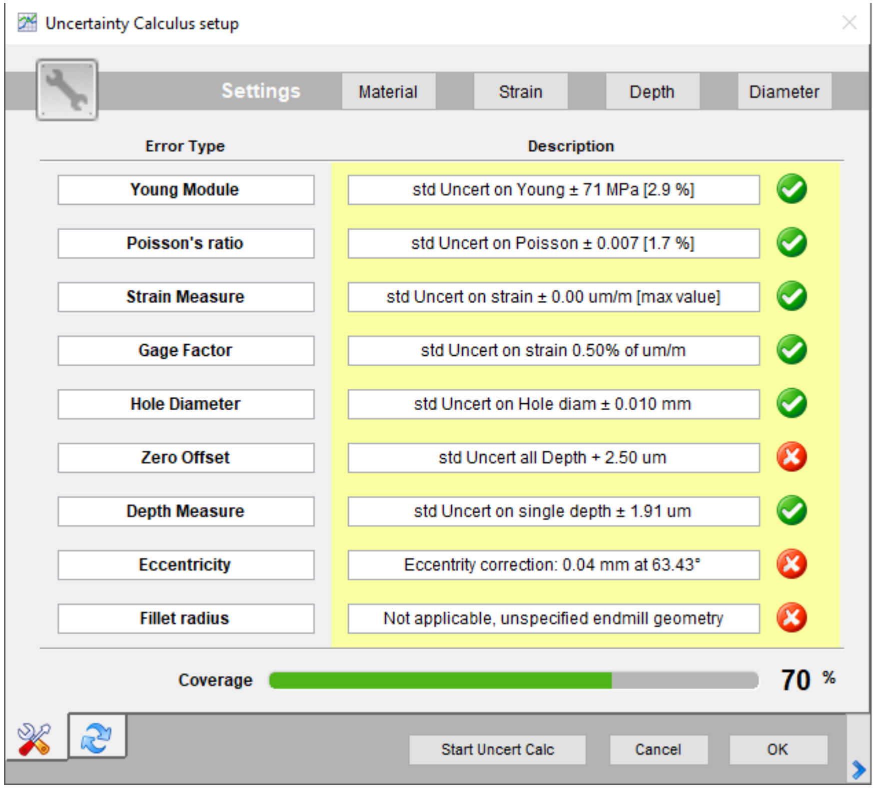
Zero Setting

How to Take into Account the Different Contributions



Expanded Uncertainty (Coverage Factor k=2)

How to Take into Account the Different Contributions



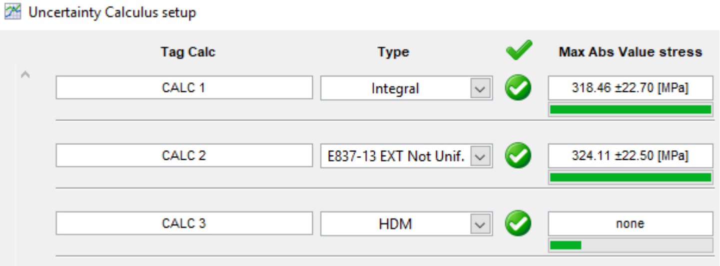
Uncertainty Calculus setup

Error Type	Description	
Young Module	std Uncert on Young ± 71 MPa [2.9 %]	✓
Poisson's ratio	std Uncert on Poisson ± 0.007 [1.7 %]	✓
Strain Measure	std Uncert on strain ± 0.00 um/m [max value]	✓
Gage Factor	std Uncert on strain 0.50% of um/m	✓
Hole Diameter	std Uncert on Hole diam ± 0.010 mm	✓
Zero Offset	std Uncert all Depth + 2.50 um	✗
Depth Measure	std Uncert on single depth ± 1.91 um	✓
Eccentricity	Eccentrity correction: 0.04 mm at 63.43°	✗
Fillet radius	Not applicable, unspecified endmill geometry	✗

Coverage 70 %

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

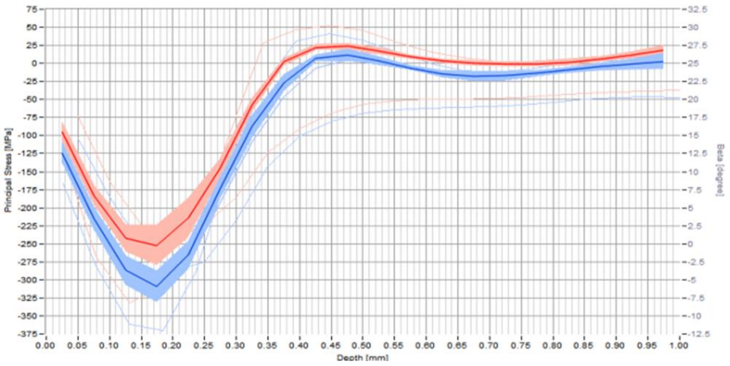
Calculation setup:

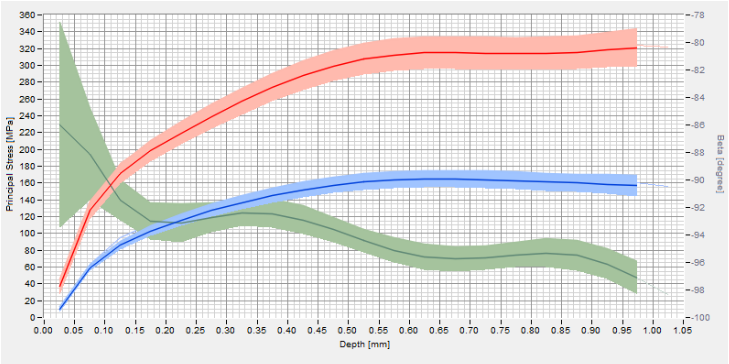


Uncertainty Calculus setup

Tag Calc	Type	✓	Max Abs Value stress
CALC 1	Integral	✓	318.46 ±22.70 [MPa]
CALC 2	E837-13 EXT Not Unif.	✓	324.11 ±22.50 [MPa]
CALC 3	HDM	✓	none

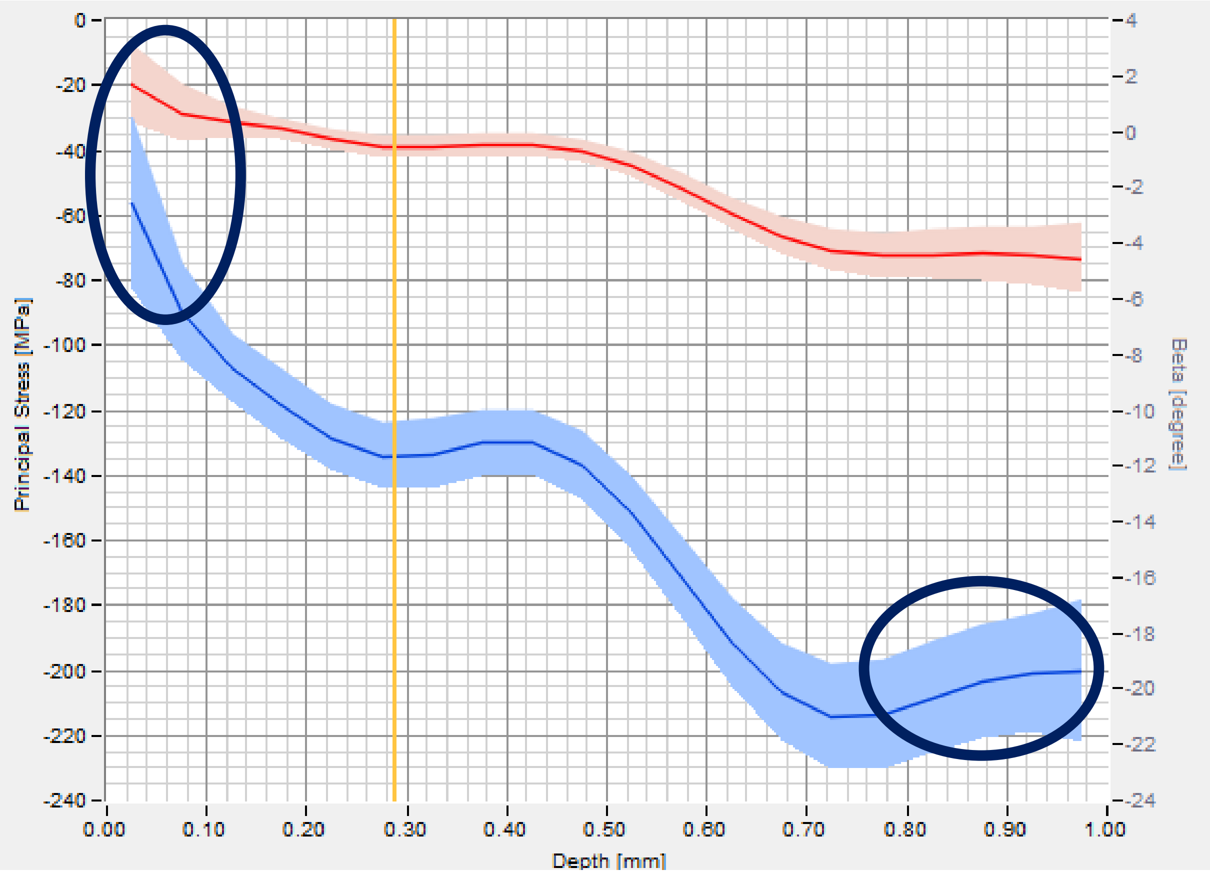
Typical test results:





Examples and Typical Test Results

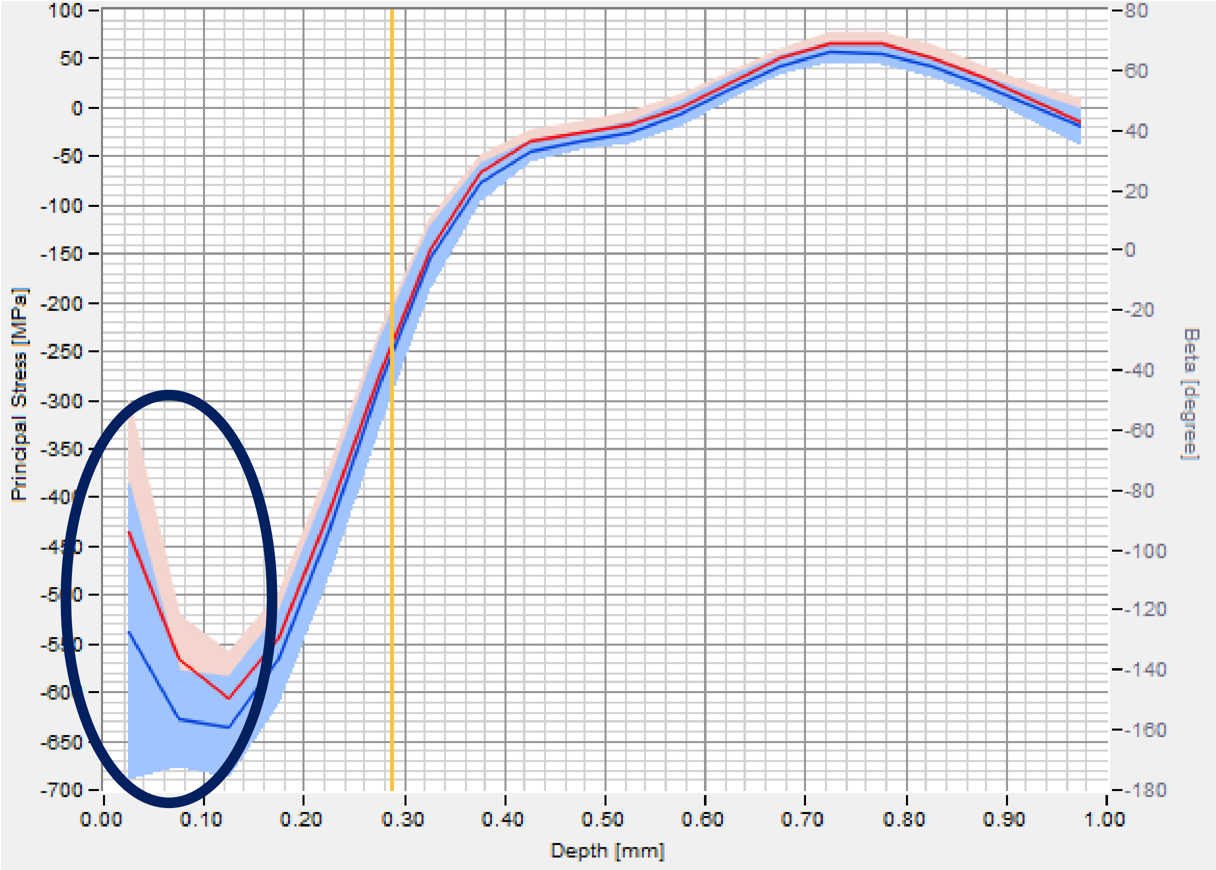
RAILWAY LINE STEEL – LOW CARBON, HOT ROLLED, LOW COOLING RATE



Generally, the **maximum** values of uncertainty are close to **surface** and at the **end** of the depth of analysis (after 0.8mm in standard conditions), where the sensitivity of the method is lower.

Examples and Typical Test Results

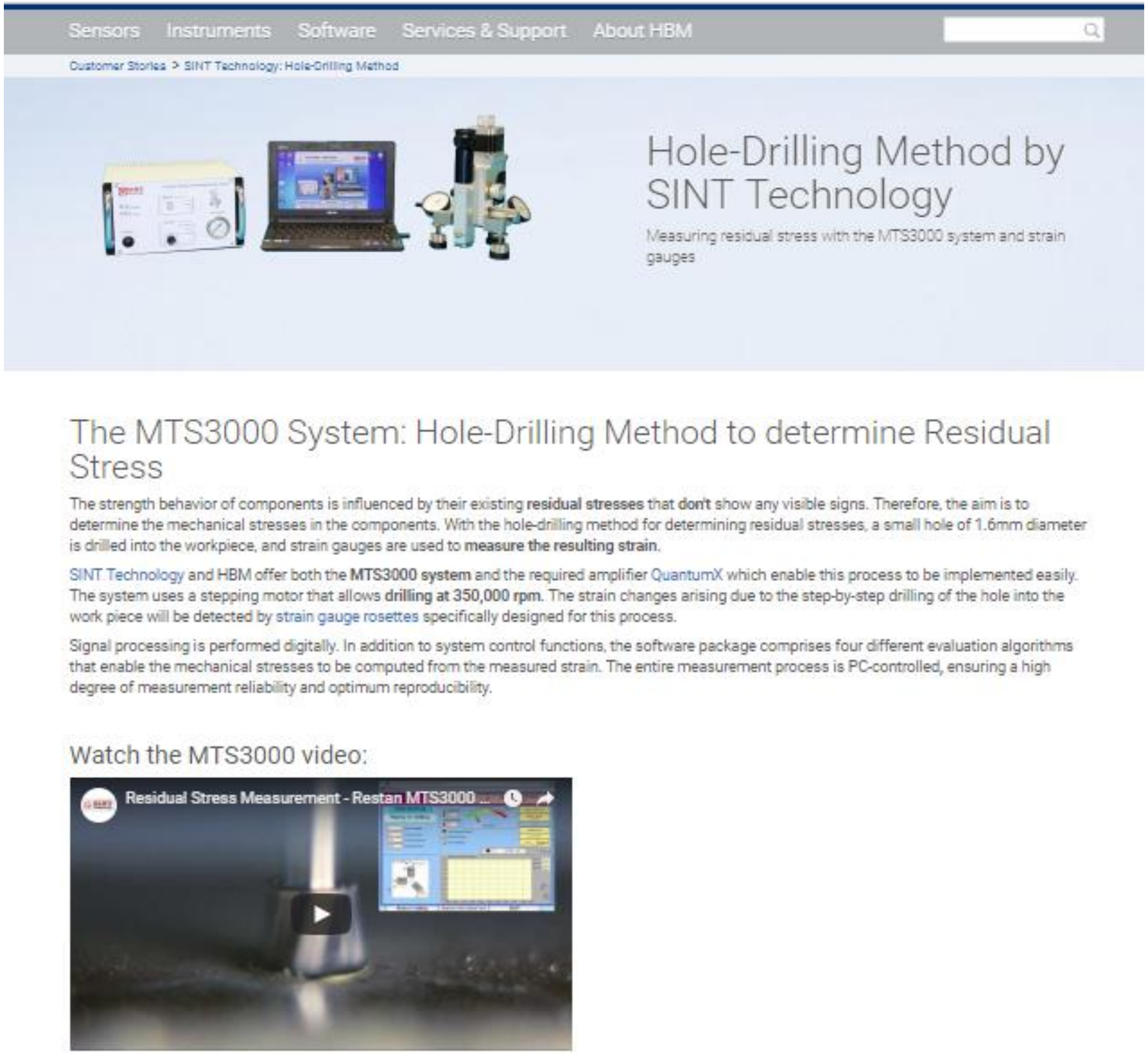
SPECIAL ALLOY STEEL – FORGED, HARDENED, TEMPERED AND **SHOT PEENED**



The uncertainty values are **higher** close to the **surface** mainly due to **fillet radius** of the end mill and to the **zero offset** (process to identify the surface before starting the measurement).

More Detailed Information

- www.hbm.com/sint



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:

More Detailed Information

- https://www.hbm.com/en/3157/webinars/

Operational Modal Analysis

Wednesday, November 20, 2019 **10:00 AM CET** **online**

Operational Modal Analysis (OMA) is used instead of Classical Modal Analysis (CMA) for accurate modal parameter identification under actual operating conditions and in situations where it is difficult or impossible to artificially excite the structure.
From originally being developed for modal analysis of large civil engineering structures, OMA is today also widely used for mechanical structures such as vehicles, aircraft, ships and machinery.

How to create your own weighing-application

Wednesday, November 20, 2019 **14:00 PM CET** **online**

While today's weighing indicators come with powerful functions and connectivity, it is often quite hard to implement those functions into sophisticated software of scale builders and OEMs.

In this webinar we will give an overview about the capability and requirements, step by step create a simple weighing application using this API and later use this new application to connect to a weighing Indicator in our network via WiFi.

Measurement uncertainty of force measurement

Thursday, November 21, 2019 **10:00 AM CET** **online**

In this webinar you will learn an easy method to estimate the uncertainty of your force measurements. Furthermore we show how to improve the accuracy if required.

www.hbm.com

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