REAVILING THE INVISBLE: NEW APPROACH FOR INDUSTRIAL SAFETY AND REAMINING LIFE ASSESSMENT

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Abstract

Today's industry requires more reliable information on the current status of their hard assets; prognosis for continued usability of systems and better predictability of equipment life cycle maintenance. Therefore, an innovative technique for early detection of potential failure and condition monitoring is urgently required by many engineers. This document describes a novel approach to improve industrial equipment safety, reliability and life cycle management. A new field portable instrument called the "Indicator of Mechanical Stresses" (IMS) utilizes magneto-anisotropic ("cross") transducers to measure anisotropy of magnetic properties in ferromagnetic material. Mechanical stresses including residual stresses in Ferro-Magnetic parts, are "not visible" to most traditional NDT (non-destructive testing) methods. Stress build-up can be the first indicator that something is faulty with a structure. We outline the evaluation of IMS as a fast screening tool to provide structural condition or deterioration feedback in novel applications for pipelines, petrochemical refinery, and municipal infrastructure.

Key words: Indicator Mechanical Stresses (IMS), Mechanical Stress detection and classification.

1. INTRODUCTION

Engineers can design structures for certain strength requirements. They can determine the greatest theoretical stress that the structure can withstand, and also define "fitness for service". However, in most cases, these are estimates only.

Conventional NDT methods have been used to assist in determining defects for various applications. These gross effects are easily detected when regular, code compliant inspections are performed. What about to reveal conditions of metal like stresses? The stresses in the mid-section are most critical for future defect development.

How can we assure the quality and safety of industrial equipment performance? What about early diagnostics for preventive maintenance or remaining life prediction? Measuring these conditions and satisfying these requirements may require another approach.

Indicator of Mechanical Stresses (IMS) can deliver better information on condition monitoring. not the search for defects, but for the condition of deterioration of metal object, to estimate and monitor of build-up of residual stresses, their concentration and gradient, which may lead to ultimate failure of the structure. The IMS can provide engineering important feedback on part stress condition and system criticality.

It is important to remember the definition of NDT (detection or measurement of the properties, integrity of parts, assemblies or structures without impairing their ability to assure safety of operation) and that each NDT technique has advantages and limitations.

This fast and reliable measurement of mechanical stress is rapidly becoming a globally accepted as complimentary technique to basic NDT methods like Radiography (RT), Ultrasonic (UT) and others.

2. BASIC PRINCIPLE OF STRESS-STRAIN DIAGRAM

The Stress-Strain diagram presented graphically the relations between Ultimate Tensile Strength (UTS, the maximum stress that a material can withstand) and "necking" (breaking) as well as differences between the engineering stress (curve A) and the true stress (curve B). Generally, linear stress–strain relationship up to point 2 (Fig. 1) is the elastic region. After point 2 (yield point), the curve typically decreases but the deformation continues. The stress increases on account of strain hardening (area 4) until it reaches the ultimate strength, (point 1). (Poisson contraction). However, beyond point 1 a neck forms (area 5) where the local cross-sectional area decreases more quickly than the rest of the sample resulting in an increase in the true stress. In a ductile material the necking becomes substantial and causes a reversal of the engineering stress-strain curve (curve A); the engineering stress (A) is calculated versus true stress (B)

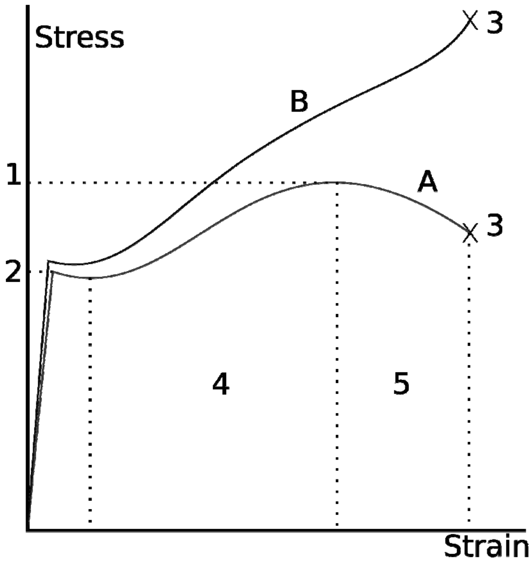


Fig 1. Stress–Strain typical curve: 1. Ultimate strength, 2. Yield strength, 3. Fracture, 4. Strain hardening region, 5. Necking region with breaking (point 3)

3. PRINCIPLE OF MECHANICAL STRESSSES, INTRODUSING IMS

The principle of magneto-elastic effect in materials (ferromagnetic materials change magnetic properties under the influence of mechanical stress) is used to build magneto-elastic and magneto-anisotropic indicators, including Indicator of Mechanical Stress, IMS.
Standard approaches to solving inspection challenges and ignoring certain physical phenomena like Lorentz force (the combination of electric and magnetic force on a point charge due to electromagnetic fields) have been long time obstacles for the widespread implementation of electromagnetic techniques in practice. It is known that the upper layer (0.2 mm) of metal has a typical stress conditions due to various stress influences like oxidation, mechanical micro-scratches, etc. Thus, some difficulties accrue in applications, for example, devices based on effect of Barkenhausen. Another reason for low confidence of measurement of mechanical stresses using electromagnetic fields indicators is magneto-mechanical hysteresis and attempts to get the result by one of the parameters of hysteresis loops (for example, based only on coercive force σ or only on residual induction B).
Any relationship between B and σ has a point inverse relationship after which the connection between B and σ become reverse, i.e. the same level of output signal can be received for two different mechanical stresses. When a steel structure which had suffered numerous mechanical changes (including local plastic deformation) in the process of preparing and mounting is, testing with conventional "stress-meters" which often provide false results.
This connection between mechanical stresses and magnetic properties called magneto-elastic sensitivity (**Λ**): where **B** is the magnetic induction and **σ** is mechanical stress (load)

$$\Lambda=\partial B/\partial\sigma \qquad (1)$$

The operating principle of magneto-anisotropic converter is based on effect of rotating magnetic induction vector B in the primary measurement coil. The voltage U at the output of the measuring coil ω is described by the formula

$$U = KB_c S_0 f_{\Pi} \sin \beta\omega \tag{2}$$

where B_c - average value of induction; S_0 - area covered by windings;

K- coefficient proportionality; f_{Π} - voltage frequency.

β - angle between the vector measuring winding ω_2 and magnetic induction B;

$$\tau_{\max} = \frac{\sigma_1 - \sigma_2}{2} \geq \sigma_T \tag{3}$$

Magneto-anisotropic ("cross") transducers used in IMS are two mutually-perpendicular U-shaped coils one is an activation coil and the other coil is a measuring coil. Transducers measure anisotropy of magnetic properties in ferromagnetic metals under external load using Magneto-elastic converters within the limitations of equipment. IMS measures Electromotive Force (EMF) by inducing a magnetic field which is generated by the excitation coil and picked up by the receiving coil, 2 perpendicular magnetic circuits in the probe (transducer). If material has isotropic magnetic properties, EMF induced in measuring coils mutually compensated and the output signal is Zero (well balanced magnetic field). If there is anisotropy of magnetic properties, unbalance of EMF occurs which results in appearance of output signal with values dependent on the value and orientation of main mechanical stresses upon the surface of metal being tested by detecting Mechanical Stress Concentration (MSC) and the difference of Principal Mechanical Stresses (DPMS).

IMS results are dimensionless, i.e. qualitative comparison (less-than-equal).

To assess the conditions and operational risk, it is not-so-important to find stresses but their concentration and rate of change of stress (gradients).

IMS allows identification of MSC and gradients to show the exact coordinates and quantify their development without any additional measurements.

Laptop required for results' processing, evaluation and storage

Fig. 2 Indicator of Mechanical Stresses (IMS), probe (transducer) and 2 calibration rings.

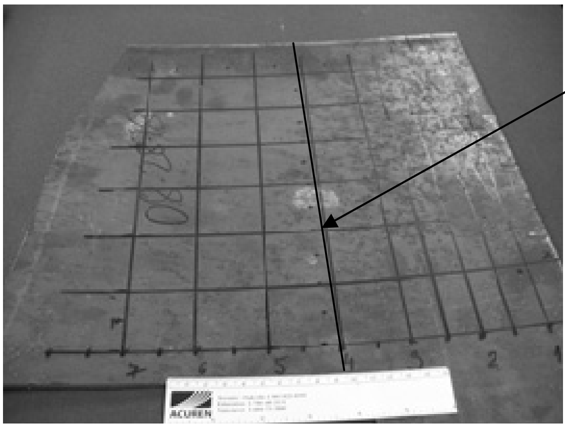
4. SOME OF STUDY CASES

Selected cases below are provided to clarify applications and benefits using IMS as a tool to measure quality of welding, stress release etc. It can also be used for monitoring processes, safety or serviceability; or as part of ISI or Preventive Maintenance, and early diagnostic for the aging construction. IMS could also be used for research and more in depth investigation of stress level inside the part

Generally acceptable criteria for the stress gradient (as recommended by designer for 10 mm thickness, non-nuclear applications and strongly depends on metal conditions, without external/internal stresses). To be used with care.

4.1 Bended plate

Development of the stress level in bent plate (popular examination).
The randomly selected plate 200 x 250 mm 10 mm thicknesses was measured for residual the stress level, bended, flatten and measured again after been bended (bending along the central line, X4) .



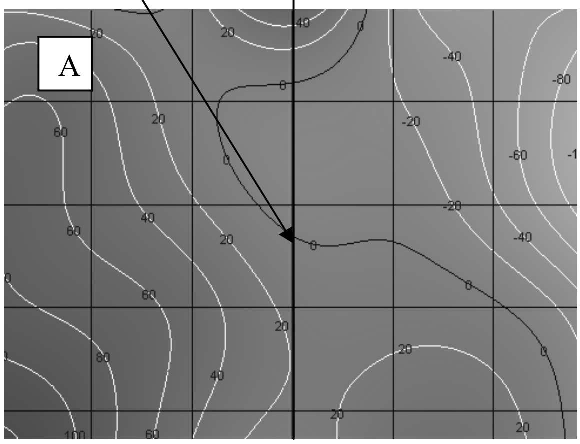
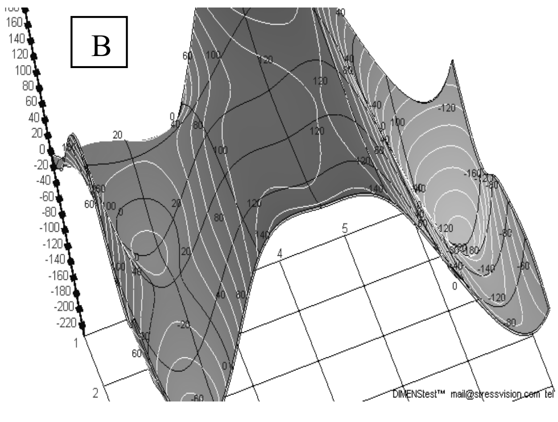
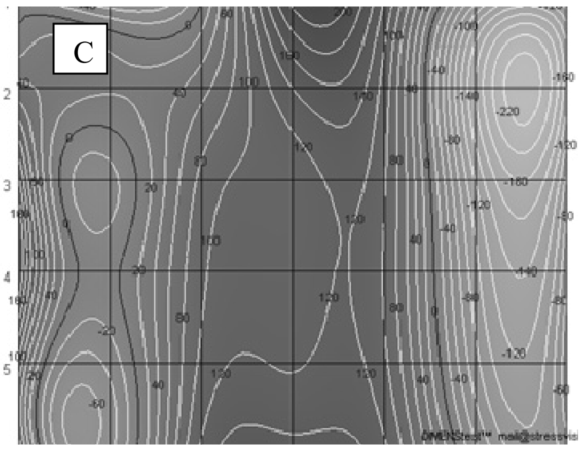


Fig. 3 Plate view

Fig. 4 Indications before (A) and after bending (B, C)





Results evaluation
Build-up of residual stress development is clearly demonstrated and no additional explanations are required.

4.2 Welded pipe 6” diameter, 6 mm thick, test piece with known defects

Fig. 5 General view of Pipe

Defect 1, start-stop. Gradient 450 is considered as critical (defects could have been already developed) confirmed by UT as approx. 5mm.

Defect No.2: pinhole with 1mm diameter (measured by UT) versus 2-3 mm by IMS at X=3.8 and Y=4.5. Gradient of 450 is considered as critical

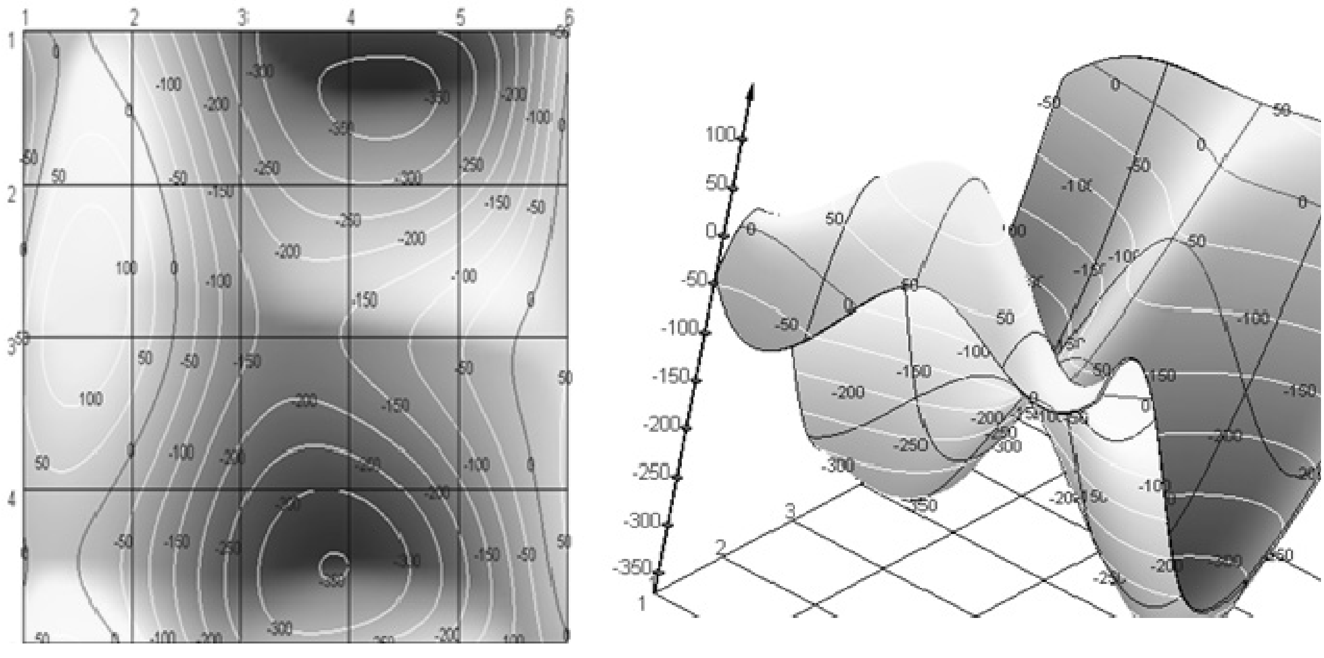
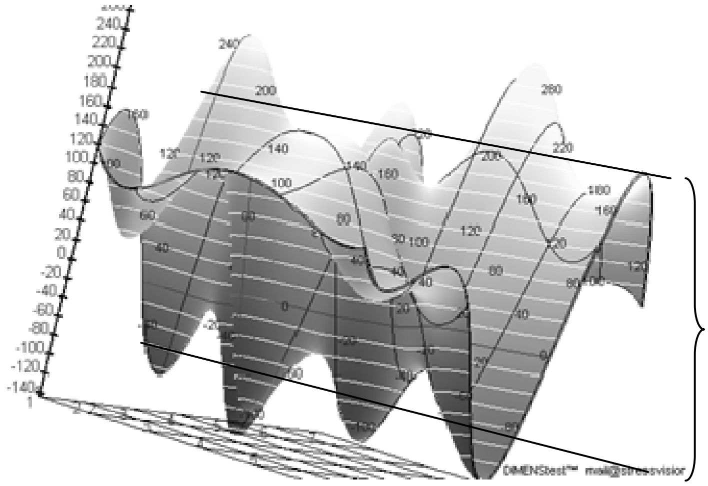


Fig. 6 2D result of Stress mapping and 3D result

The high stress gradient and concentration of IMS results confirmed exact location of defects found by UT. Stress map shows a much larger area of concern around the know defect.

4.3 Conformity of the quality stress release by Heat Treatment (HT) process

Two steel plates 10 mm thicknesses were welded with low quality of welds. The weld area was marked and measured for stress concentration and gradient before and after of the Heat Treatment 520ºC for 8.5 hours (standard process). After the Heat Treatment process, the plate was measured again using same mapping grid.



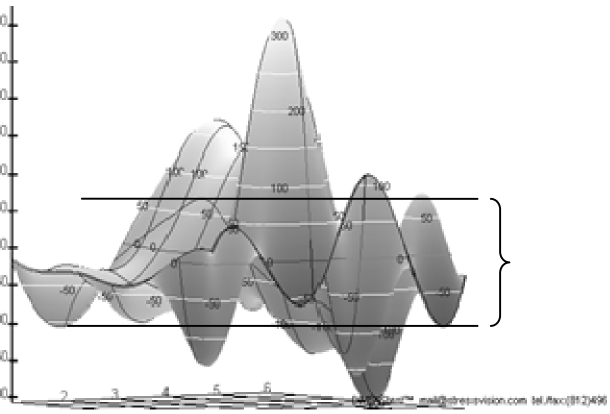


Fig. 7 Stress diagramme before HT After the HT

Results are showing high stress level before the HT and considerable stress release after the treatment. The Heat Treatment process was done sufficiently and full stress release.

4.4 Case of the low quality Heat Treatment (HT), incomplete process

Similar to the previous case, plates were welded and measured for stress concentration and gradient before and after incomplete process (520ºC for 3.5 hours instead of 8 hours).
Results of the gradient of Mechanical Stresses before HT was about 450 and after was only 400
Low quality of HT was resulting in only minor improvement of stress release and only on surface and sub-surface.
Hardness was not measured but very likely would show some hardness improvement (surface improvement).

4. 5 In-Service Inspection, LPG Storage tank (under pressure of 15 atm.)

Results were none conclusive due to unsufficient references of stress build-up.
By monitoring after 9-12 months we could create information data on stability (or increase) of stress in critical areas and to make a proper assessments.

4.6 Bridge Crane, 20 tons (serviceability of the aging item)

Technical information: Lift max 20 tons, length 22m, age over 20 years
Purpose: To investigate the condition of mechanical stresses and to evaluate crane's life extension (ISI) prior to de-commissioning.
Selected areas (one area near the driving wheel and another area at the center of the crane frame) were measured before the load test then under load of 10t, 20t, immediately after removal the max load and on the next day.

Fig. 8 Crane, general view

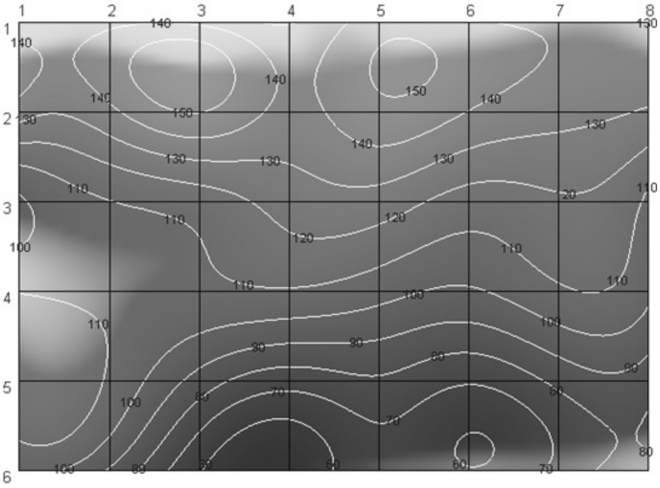


Fig. 9 Crane, center beam– without load and

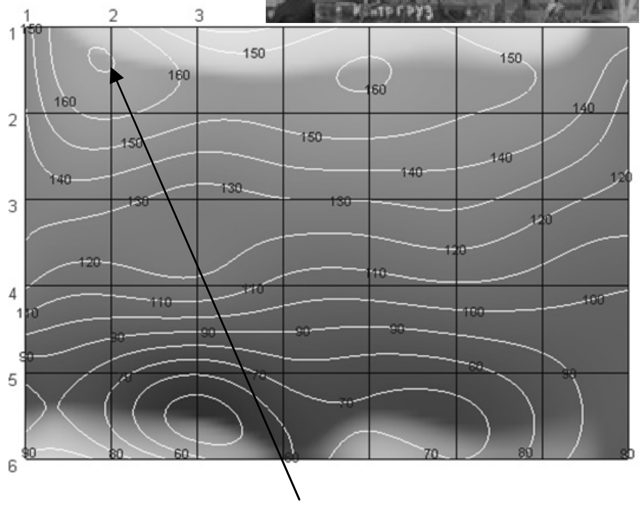


Fig. 10 Under 10 tons load

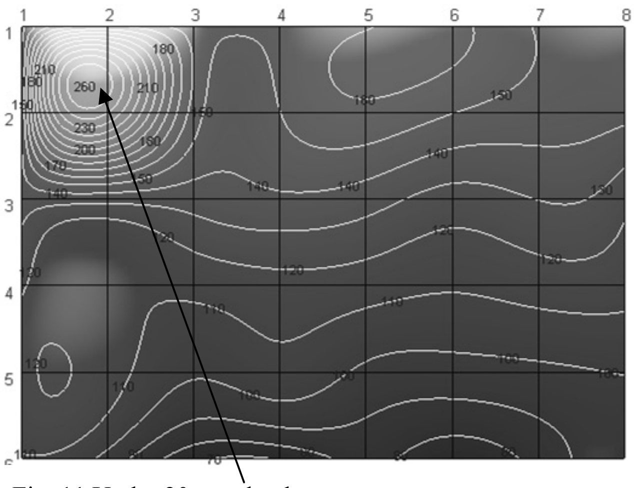


Fig. 11 Under 20 tons load

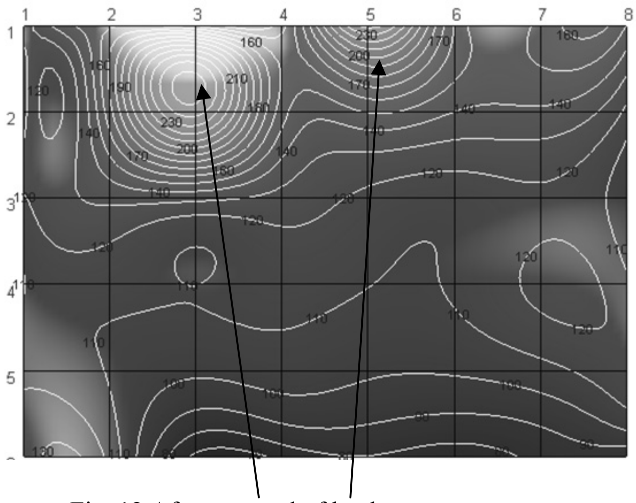


Fig. 12 After removal of load.

Recommendations were to extend crane's operation life for another 9 months, to limit the working load to 10 tons and to monitor stress conditions again after 9 months.
Today, 7 years after the initial experiment, the crane is operating safely with max 10 ton load and monitoring every 9 months. Cost of a new crane is about 3 Million USD

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5 Conclusions

1 The IMS “StressVision” instrument may allow asset owners to avert stress related equipment failure.
2 Engineering can proactively make decisive calls on equipment “fitness for service” based on the location and concentration of residual stresses and electromotive forces found in metal structures and welds.
3 IMS “StressVision” can be used independently as a screening tool; or preferably, as a forerunner to/and in conjunction with conventional NDT methods to target suspect areas that require more examination. Surface, sub-surface and volumetric stresses can be determined, all of which could be critical for equipment life expectancy.
4 The IMS was originally designed for ferrite metals with thickness (depth) of up to 12 mm. Additional investigations are required for any changes of metallurgical composition or thickness higher than 12 mm to determine acceptable stress levels.
5 The various technical and financial benefits of using IMS have been proven in bridge, crane, pipeline, clad material, offshore platform and other experimentation. This research qualified the stress release due to Heat Treatment and demonstrated that “StressVision” could be used to categorize ineffective heat treat process. This could be especially important in pipeline integrity.
6 Further research is recommended for all applications (thicker parts, special alloys etc.) to assure relevant results, discover additional applications or to test the limits of the IMS “StressVision” system.
7 Experimental studies presented in this report confirm the accuracy, repeatability and reliability of IMS in the selected application conditions.
8 IMS promises to be a valuable evolution in NDT, by veiling the invisible forces that could influence equipment failure.
9 On certification and calibration. For the first time in the worldwide, the Mendeleyev Scientific and Research Institute for Metrology (VNIIM), has awarded the certificate of Calibration (certificate of competence) for device measuring of mechanical stresses to the “Indicator of Mechanical Stresses” StressVision. Correlations between results of StressVision (f, no units) and value mechanical stress σ (MPa) measured by VNIIM as Corr. (f, σ) =0.986 (almost 100% correlation!).