Revealing the Stresses – New Approach for Industrial Safety, Reliability and Residual Life Assessment

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Abstract
Today’s technology demands higher emphasis on safety of industrial components, accurate measurements with intelligent prognosis on condition monitoring, reliable residual life assessment and life extension techniques consistently good to ensure Fitness-for-Service. This presentation highlights a new approach for industrial safety by using innovative technology, the Indicator of Mechanical Stresses (IMS). Not the search for defects but for residual mechanical stresses and their deterioration of asset’s stress condition and level of criticality. The main goal is to estimate the safety of operation and to monitor the condition, the remaining operational life of the asset and to draw conclusions based on the practical results of the structure in question, mainly for ferromagnetic steel.

Keywords: Early detection of residual stresses, monitoring and classification, Indicator Mechanical Stresses.

1. Introduction

Engineers can design structures to certain strength requirements. They can determine the greatest theoretical stress that the structure can withstand, 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. How to reveal conditions of metal like stresses? The stress in the mid-section is most critical for further 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? Detecting these conditions and satisfying these requirements may require another approach. [1] Indicator of Mechanical Stresses (IMS) can deliver better information on condition monitoring. Not the search for defects, but for the condition of assets deterioration, to estimate and to monitor 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.

2. Principle of mechanical stress measurements

2.1 The principle of magneto-elastic effect in materials (ferromagnetic materials change magnetic properties under the influence of mechanical stress) is used to develop 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 the effect of Barkenhausen.

2.2 Any relationship between B (residual induction) and $\sigma$ (coercive forces) has a point inverse relationship after which the connection between B and $\sigma$ become reverse, i.e. the same level of output signal can be received for two different mechanical stresses. When steel structure which had suffered numerous mechanical changes including local plastic deformation in the process of preparing and mounting, conventional “stress-meters” often provide false results.

This connection between mechanical stresses and magnetic properties called magneto-elastic sensitivity ($\Lambda$): where B is the magnetic induction and $\sigma$ is mechanical stress (load)

$$\Lambda=\frac{\partial B}{\partial \sigma}$$

(1)

Principle of operation magneto-anisotropic converter based on effect of rotating magnetic induction vector B in the primary measurement coil. The voltage U at the output of the measuring coil $\omega$ is described by the formula

$$U = KBcS_o f_{\omega} \sin \beta \omega$$

(2)

where $B_c$ – average value of induction; $S_o$ – area covered by windings; K- Coefficient proportionality; $f_{\omega}$ – voltage frequency; $\beta$ – angle between the vector measuring winding $\omega_2$ and magnetic induction B;

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

(3)

3 Introducing Indicator of Mechanical Stress, IMS

3.1 Magneto-anisotropic ("cross") transducers used in IMS consist from two mutually-perpendicular U-shaped coils activation and the measuring coils. 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 (CMS) and the Difference of Principal Mechanical Stresses (DPMS). [2]

3.2 Indicator of Mechanical Stresses (IMS) includes data collector and probe (transducer). Laptop required for results processing, storages and reporting.
3.3 Since IMS belongs to Qualitative techniques, results are dimensionless, i.e. qualitative comparison (less-than-equal).
To assess the conditions and operational risk, it is important to find the stresses but also to know their concentration (CMS) and rate of change of stress (DPMS).

4. Study cases (selected) [3], [4]

4.1 Case of Clad Metal
Clad-metal plate (a.k.a. bi-metal) with the main interest evaluation of “metal to metal bonding”.
Foreign Object Body, FOB (metallic nut) introduced prior to the cladding to create an artificial delamination.
Rounded yellow circle mark (Fig. 4) is identifying boundaries of lamination as detected by ultrasonic technique using normal probe versus high stress areas detected by IMS.
Note: Concentration of Mechanical Stress, CMS values are clearly presenting the FOB’s area of high stress within the area as identified by UT as a lamination.

Fig. 2. Clad metal
Fig. 3. Data collection
Fig. 4. Results by UT

Fig. 5. Cartogram by IMS

4.2 Steam Generator, RostovNPP
Pipe dia. 180 mm, wall thickness 10 mm, High Cr steel.
Before the pore repair (detected by UT) and after repair and HT
Comments on results from site (NPP):
Max PDMS 650, 200 base metal, outside HAZ vs. PDMS (-) 450 at X=6, Y=7.
This indication was detected by UT as pore defect.
After weld’s repair and the heat treatment (HT) results were as follows. Please note the X6 line representing the center of the weld after repair and HT! Confirming the high quality of HT and full stress relief.
In addition.
Very impressive test results conducted by a team of engineers RNPP investigating correlation of strain (tensile testing with controlled load) and stress (measures by IMS) for given high-alloy heat resistant steel, the same material which has been used for the pipe.
Experimental Stress-Strain diagram is very similar in shape to the conventional diagram and very useful now for evaluation results received by IMS for this specific steel. Currently this team continue with research on other critical pipe joint and comparing results by IMS compliance with UT and RT requirements.

4.3 Fuel storage tank, 20 years old, after the earthquake, newly repainted, partially full. (Old paint removal was probably by chemicals).
Comments:
1. High concentration (CMS) in sub layer 0-3 mm in all inspected areas compare to the sum of layers and second (6 mm) layer could be due to chemical surface treatment (removal of old paint) with possibility inducing Hydrogen Embrittlement.
2. It was recommended to verify results (Area 3, T-joint) of the vertical weld X3 by UT method due to severity of high stress (possible strong internal defect based on results CMS by slicing).

4.4 Pipe with partially welded groove, Wall thickness 8 mm

Fig. 16. Pipe, general view
Fig. 17. DPMS sum of layers
Fig. 18. DPMS, Slice sub-surface (0-3 mm)
Fig. 19. DPMS, Slice up to 6 mm

Comments:
1. The Zero line (Red) of DPMS indicates change of direction Mechanical Stress (Compression and Tensile) and is a vital for the results assessment’s process.
2. The Sum of layers (Fig 17) is for brief review only and showing if there is any issue with stresses in the area of interest (the weld and HAZ).
3. The Subsurface (Layer 0-3 mm, Fig 18) shows change of directions due to heating (welds) but signals fluctuation indicates that the weld of “low quality”.
4. The slice in-depth (Layer 6 mm, Fig. 19) indicates that the metal was not “heated” by the weld which could be lack of root penetration, no weld at the bottom.
5. The visual inspection confirmed that the weld inside the pipe was not welded, only some spot-welds.
6. This study case demonstrates the quick and precise way to analyse the quality of weld (to be confirmed by conventional NDT method).

4.5 Conformity the quality of stress relief by Heat Treatment (HT) process
Two plates 10 mm thicknesses were welded (V weld)
The welded area and HAZ were marked by grid and measured for stress concentration and gradient before and after of the Heat Treatment 520°C for 8.5 hours. After the Heat Treatment process, the plate was measured again using same mapping grid showing substantial stress relief.

4.6 Pipe dia. 180 cm, 10 mm wall thickness
Weld inspection, Butt Weld

Clearly visibly stress reduction after the HT based on lower DPMS after HT
Comments:
1. High Gradient (DPMS) and CMS at the area X3 (along the weld) and very high at Y4-7.
2. Using Layer slicing mode, IMS results presents high gradient of mechanical stress (DPMS) along X3 with pick (areas of main concern) at Y6 and very high concentration (CMS) of Layer 0-3 mm indicated that the main concern of stress build-up is at the nearby surface.
3. Interesting to note classical stress distribution at welded and near weld areas proving the HAZ (X2 and X4) distribution from high at X3 to normal X1 and X5.
4. RT results confirms findings of IMS. There was almost full length Lack of Root fusion but high stress region is much bigger than the detected defect.
4.7 Certification of StressVision

After thorough investigation, the certificate on correlation of mechanical stress results by IMS was issued by the Mendeleyev’s Institute of Metrology, VNIIM, (St. Petersburg) with results correlation of $\sigma=0.986$ or 98.6% accuracy.

5. Conclusions

5.1 The IMS “StressVision” is a unique addition to the NDT techniques. It provides pre-emptive vision of potential asset's failure by providing reliable information and accurate results of the stress status of the item.

5.2 Can be used independently (as a screening tool) or complementary to conventional NDT techniques to confirm critical findings.

5.3 Using comparison approach (“before and after”) will assist for more reliable and more accurate results identification and improves the credibility of investigator.

5.4 Experimental studies presented in this report confirm the accuracy, repeatability and reliability of IMS.

5.5. The Certificate of Calibration (certificate of correlation) was awarded for device measuring mechanical stresses, IMS. Correlations between results of StressVision ($f$, no units) and value mechanical stress $\sigma$ (MPa) measured by VNIIM was Corr. ($f$, $\sigma$) =0.986 (almost complete correlation!).

5.6 This innovative technique promises to be the next evolution in NDT, by going beyond basic NDT techniques to resolve the unseen forces that influence aging asset’s failure.

5.7 IMS was originally come to service mainly Gas and Oil industries, especially pipelines. Further research recommended like specific for applications for special alloys and to discover the limitations of the Indicator of Mechanical Stresses “Stressvision” device.

6. References