Revealing the Invisible: A New Approach for Enhancing Industrial Safety, Reliability and Remaining 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 “IMS (indicator of mechanical stresses)” 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; for example, radiography and ultrasonic inspection. Stress build-up can be the first indicator that something is faulty with a structure. This can be the result of a manufacturing defect; or as assets age and fatigue, stress loads can become unevenly distributed throughout the metal. 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, cranes, and municipal infrastructure.

Key words: IMS, mechanical stress concentration, mechanical stress gradient, 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 calculated estimates only.

Corrosion, hostile environment, workmanship, poor welding, inadequate service and maintenance, aging equipment could lead to future structural issues.

How can we assure reliable industrial equipment performance? What about early diagnostics for preventive maintenance or remaining life prediction? How do we validate the quality of a heat treatment process and stress release? And many more unanswered questions. Identifying these conditions and satisfying these requirements may require another approach.

Conventional NDT (non-destructive testing) methods (such as radiography and ultrasound inspection) have been used for many different applications to elucidate manufacturing, corrosion and age related defects. These gross effects are easily detected when regular, code compliant inspections are performed. So, how do we reveal conditions in metal, like mechanical stresses? Especially stresses within the material volume, which can be the most critical for future structural failure.

How do we estimate and monitor of build-up of residual stresses, their concentration and gradient,
which may lead to ultimate failure of the structure?

IMS (Indicator of mechanical stresses) can provide important feedback to engineering on stress conditions and deliver better information for condition monitoring and about system criticality [1].

2. Basic Principle of Stress-Strain Diagram

A review of the stress-strain diagram, including UTS (ultimate tensile strength) the maximum stress that a material can withstand before “necking” (fracture or breaking), would seem appropriate. Generally, a linear stress-strain relationship (Fig. 1) is the elastic region. After this point (yield point), the curve typically decreases but the deformation continues. The stress increases on account of strain hardening until it reaches the ultimate strength, (point U). However, beyond point U a neck forms here the local cross-sectional area decreases more quickly than the rest of the sample (Poisson contraction) 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. The engineering is classical calculated versus true stress.

3. Principle of Mechanical Stress Measurements, Introducing 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 the 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 change due to electromagnetic fields) have been long time obstacles for the widespread implementation of electromagnetic techniques. It is also known that the upper layer (0.2 mm) of metal has a typical stress condition due to various stress influences like oxidation, mechanical micro-scratches, etc. Thus, some difficulties can accrue in certain applications, for example, using devices based on Barkhausen effect. Another reason for low confidence in mechanical stress data using electromagnetic field indicators is magneto-mechanical hysteresis. Some analysis methods rely on only one of the parameters of hysteresis loops (for example, based only on coercive force or \( \sigma \) only on residual induction \( B \)).

Any relationship between \( B \) and \( \sigma \) has a point inverse relationship after which the connection between \( B \) and \( \sigma \) becomes reversed, i.e. The same level of output signal can be received for two different mechanical stresses, tensile deformation and compressive deformation.

When a steel structure which had suffered numerous mechanical changes (including local plastic deformation in the process of preparing and mounting), testing with conventional “stress-meters” may 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) (1):

\[
\Lambda = \frac{\partial B}{\partial \sigma}
\]  

The operating principle of a magneto-anisotropic converter is based on the effect of a rotating magnetic induction vector \( B \) in the primary measurement coil. The voltage \( U \) at the output of the measuring coil \( \omega \) is
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described by the Eq. (2):

\[ U = KB \frac{S}{c} f_\beta \omega \sin \beta \theta \]  

where,

- \( B \) = average value of induction;
- \( S \) = area covered by windings;
- \( K \) = coefficient proportionality;
- \( f_\beta \omega \) = voltage frequency;
- \( \beta \) = angle between the vector measuring winding;
- \( \omega \) = magnetic induction.

The IMS consists of an exciter/receiver instrument with built in data file storage, probe (transducer), and a computer (with data analysis software, which is required for mass data processing and offline data storage) [2]. The magneto-anisotropic (“cross”) transducer utilized with the IMS consists of two mutually perpendicular U-shaped coils; one activation (or excitation) coil, and a measuring (or receiver) coil. Transducers measure anisotropy of magnetic properties in ferromagnetic metals under external load using magneto-elastic converters (within the limitations of equipment). IMS measures EMF (electromotive force) by inducing a magnetic field in the metal which is generated by the excitation coil and stress related EMF is then picked up by the receiving coil. There are two perpendicular magnetic circuits in the probe. If the material has isotropic magnetic properties, EMF induced in measuring coils is mutually compensated and the output signal is zero (well balanced magnetic field). If there is anisotropy of the magnetic properties, an imbalance of the EMF occurs. This results in an output signal with values dependent on the value and orientation of the main mechanical stresses upon the surface of the metal being tested. The instrument detects the MSC (mechanical stress concentration) and the DPMS (differential of principal mechanical stresses).

IMS results are dimensionless, i.e., a qualitative comparison (no value).

To assess the conditions and operational risk, it is not so important to enumerate the stresses, but the MSC (mechanical stress concentration) and rate of change of stress (gradients) are very important parameters.

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

Certification of correlation: For the first time worldwide, the Mendeleyev Scientific and Research Institute for Metrology (VNIIM), Russia, has awarded the certificate of calibration (certificate of competence) for a device measuring mechanical stresses to the IMS stress vision.

Correlations between results of IMS stress vision (f, no units) and value mechanical stress \( \sigma \) (MPa) measured by VNIIM as Corr. \( (f, \sigma) = 0.986 \) (almost 100% correlation).

4. Results and Discussion

Selected case studies below are provided to clarify applications and benefits of using IMS. IMS is 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 (life extension) or preventive maintenance, and early diagnostics for aging assets [3]. IMS could also be used for research and more complicated investigation of residual stress.

Fig. 2 IMS consists of an exciter/receiver instrument with data storage, probe (transducer), computer required for data processing and storage.
4.1 Bended Plate

Development of the stress level in bent plate (popular examination).

A randomly selected plate $200 \times 250 \times 10$ mm thicknesses was measured for residual stress level, bent, flattened and measured again after been bent.

Fig. 3 shows Plate (general view) and the stress conditions (residual stress) before the bend.

The gradient of stress level was about 200 with low MSC, normal stress conditions.

4.2 Samples with Known Defects

Defects detected by RT and UT [4, 5].

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

4.3 Conformity of the Quality Stress Release HT Process

Two steel plates (10 mm thicknesses) were welded

![Image](image_url)

Fig. 3  (a) general image of plate, (b) 2D before the bending, (c) 3D after bending, and (d) 2D images after bending.

Results evaluation:
Low residual stress level before the bend (normal conditions of the plate) and high residual stress but not critical level (gradient and concentration) after the bending.

Build-up of residual stress development is clearly demonstrated and no additional explanations are required.
Fig. 4  General view of pipe.  
Defect number 1: start-stop approx. 5mm (UT result). Gradient 450 is considered as critical (defects could have already developed).  
Defect number 2: pinhole with 1mm diameter (measured RT result) versus 2-3 mm by IMS at X = 3.8 and Y = 4.5. Gradient of 450 is considered as critical.

Fig. 5  2D result (a) of stress mapping and 3D result (b).

with low quality welds. The weld area was marked and measured for stress concentration and gradient before and after of the heat treatment 520 °C for 8.5 hours (standard process). After the heat treatment process, the plate was measured again using same mapping grid.

Results show high stress levels before the Heat Treatment and considerable stress release after the heat treatment, the HT process was done sufficiently (however, indications which are known defects, remain as a source of stress in the plates).

4.4 Case of the Low Quality HT, Incomplete Process

Similar to the previous case, plates were welded and measured for stress concentration and gradient before and after incomplete process (520 °C for 3.5 h instead of 8 h).

Results of the gradient of mechanical stresses before HT was about 450, and after was only 400.

Low quality of HT resulted in only minor improvement of stress release and only on surface and sub-surface.

Hardness testing (required by many codes as
verification that HT was done) was not measured, but very likely would show some hardness improvement (HT surface improvement).

4.5 In-service Inspection, LPG Storage Tank (Pressure of 15 Atm.)

Results were inconclusive due to insufficient reference areas of stress build-up.

Stress results may also vary during the day due to ambient temperature changes (experiment was conducted in Kenya).

By monitoring the same areas of the tank (after 9-12 months), we may be able to predict stability (or increase) of stresses in critical areas and make a proper assessment with the historical data.

Unfortunately, it was not possible to perform at that time.

4.6 Bridge Crane, 20 Tons (Serviceability of the Aging Item)

Technical information: lift max 20 tons, length 22 m, age over 20 years.

Purpose: to investigate the condition of mechanical stresses and to evaluate crane’s 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 10 tons, 20 tons, immediately after removal the max load and on the next day.

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, 5 years after the initial experiment, the crane is operating safely with max 10 ton load and with monitoring every 9 months. Cost of a new crane would be about 3 million USD and the company has 5 such cranes, very impressive performance of IMS with big financial savings.

5. Conclusions

1. The IMS stress vision 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 stress vision 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. Any changes of metallurgical composition or thickness higher than 12 mm require additional investigation 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 HT and demonstrated that “stress vision” 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 stress vision.
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.

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