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PASSIVE MAGNETIC OBSERVER IN NDE & SHM APPLICATIONS

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ABSTRACT

The paper concerns about the idea of passive magnetic observer and magneto-mechanical effects (reversible and irreversible) to non-destructive testing and monitoring of critical elements (NDE&SHM). The diagnostic task is regarding as the fast identification of overload elements, which have not broken, cracked or deformed yet (detect 1st and 2nd stage of damage). Theoretical and experimental results from evaluating the early phase of the material fatigue have been presented. Issues have been discussed on two examples (classes of diagnosis task for passive magnetic observer):

a) testing object is located only in the Earth's magnetic field;
b) testing object is located in the Earth's magnetic field and low alternating electromagnetic field.

KEYWORDS: *magneto-mechanical effects, material damage, magnetovision, NDE&SHM.*

INTRODUCTION

Effective and credible monitoring the structure is possible when actually gets to given technical problems: expected diagnostic symptoms and measuring and analytical methods (algorithms). Selection of the concept and research methods of non-destructive evaluation (NDE) or structural health monitoring (SHM) results from needs of the user - answer to a question, which the damage phase is supposed to be observed, Figure 1.

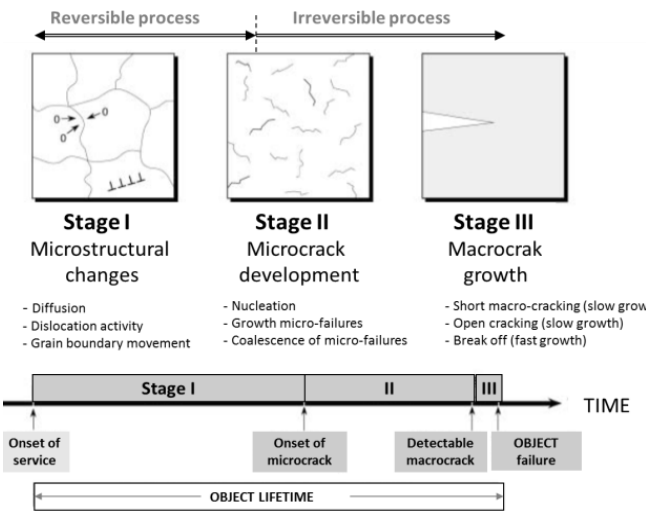

Figure 1: Continuum damage mechanics for cold working material [1]

Classical NDE methods (X-ray, eddy current, ultrasound, magnetic partial and fluorescent) specialize mainly in the detection of the 3rd phase of material damage (of opened crack, volume defects) [2]. These methods are not used for monitoring stresses level and early phase of material damage (in spite of technical existing opportunities) so they are not possibility of fatigue prognosis. These methods are very low effective to fatigue prognosis because of:

- finding the crack or other discontinuity of the structure, rather than its causes are their main task;
- lack of reliable information about real operating conditions;
- lack of knowledge about early cracking symptoms and mechanisms.

Other possible of fatigue detection based on relationship between changes in the material structure during 1st and 2nd stage of damage (before open crack, Figure 1) and subtle measurable

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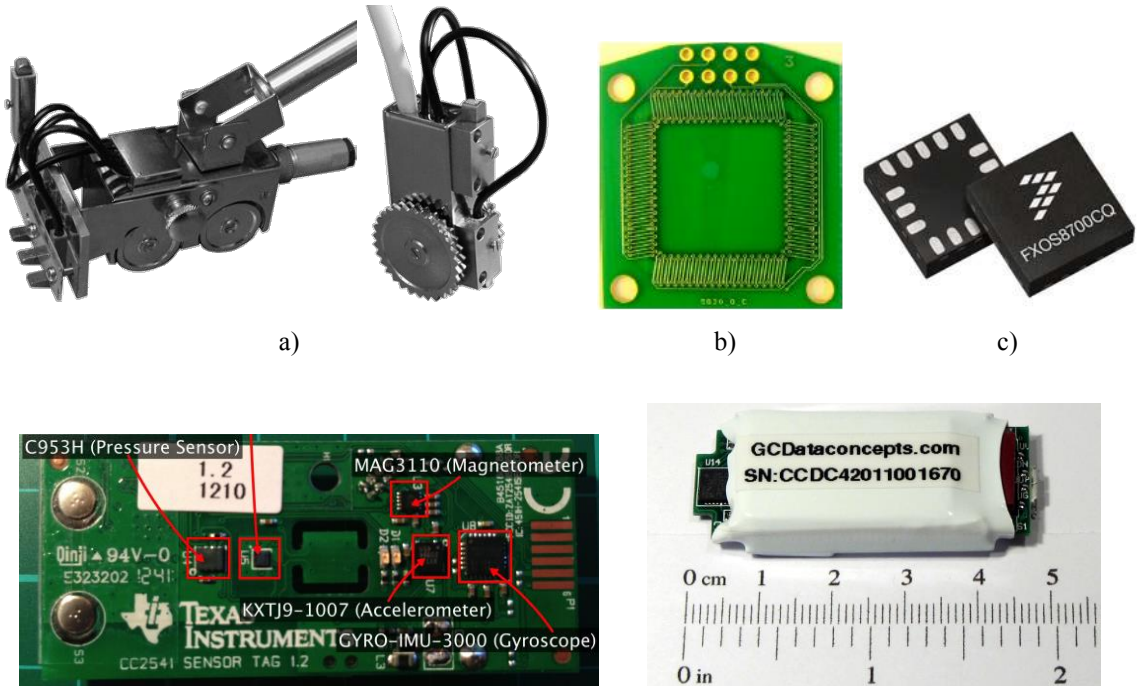
changes of parameters (diagnostic symptoms), i.e. distribution of magnetization in ferromagnetic and metastable paramagnetic materials (i.e. metastable stainless steel, which is sensitive on strain ά-martensite transformation) [3-8], which can be measured indirectly in near of the examined element by low cost vector magnetometers (fluxgate, AMR, TMR, MI, GMI), Figure 2.

The paper concerns about the idea of passive magnetic observer (i.e. the Metal Magnetic Memory (MMM) method [9, 10]) and magneto-mechanical effects (reversible and irreversible) to non-destructive testing and monitoring of critical elements (NDE&SHM applications) – Table 1. The issue is presented on examples of low-pressure turbine blades and pylons of high voltage line.



a) b) c)

d) e)

Figure 2: Model sensors applied for the measurement of the magnetic field near the diagnosing object: a) 4x2-axis and 2x2-axix fluxgate magnetometer with encoder (transmitter of moving) of Energodiagnostik Ltd company applied for NDE of welding joints according to ISO 24497 [11]; b) 2-axis fluxgate sensor of Tyndall National Institute made in the PCB technology with using Si and alloys of cobalt [12]; c) MEMS 6D E-compass sensor (3-axis magnetometer and 3-axis accelerometer, 3.0x3.0x1.2 mm) type FXOS8700CQ of FreeScale Xtrinsic company with the function of calculating magnitude of magnetic induction and acceleration vectors [13]; d) CC2541 SensorTag of Texas Instruments company (3-axis magnetometer, 3-axis accelerometer, 3-axis gyroscope, pressure sensor, temperature sensor and humidity sensor) with Bluetooth LE 4.0 as low-energy component of contactless SHM networks [14]; e) 6D platform type X8M-3 (3-axis magnetometer and 3-axis accelerometer) with 2GB data logger of Gulf Coast Data Concepts company [15]

1 THEORY OF PASSIVE MAGNETIC OBSERVER

In the macroscopic scale a constitutive law (1) is copying magnetic properties of the testing element [16]

$$\mathbf{B} = \mu\mathbf{H} = \mu_0(\mathbf{H} + \mathbf{M}) = \mu_0\mathbf{H}+\mathbf{J} \tag{1}$$

where: μ_0 – magnetic permeability of vacuum (in SI units system $\mu_0 = 4\pi\cdot10^{-7}$ [H/m]); **B** – magnetic induction [T], **H** – external magnetic field strength [A/m], **J** – magnetic polarization of material; **M** – magnetization of material [A/m].

Table 1: Objects possible to NDE&SHM with the help of the passive magnetic observer.

Diagnostic class of the object for passive magnetic observer	Class of the degradation process of material	Model objects of NDE&SHM with using passive magnetic observer
Stationary object	Cold working, low cycle fatigue (LCF), high cycle fatigue (HCF)	Railway rails, transmission pipelines, load-bearing structures of steel bridges and halls, masts, pressure cylinders
	Thermal stresses, heat affected zone (HAZ)	Welding joints, bodies of turbines
	Hydrogen brittleness, chemical and electrochemical corrosion	Fittings chemical, sea drilling platforms and wind turbines
Stationary object in electromagnetic fields	Cold working, LCF, HCF	Electricity pylons, stators and bodies of generators and electric engines
Movable object	Cold working, LCF, HCF, very high cycle fatigue (VHCF), erosion, corrosion	Vehicles, shafts, gears, bearings, blades of the compressor and low-pressure turbine
	Creep, thermo-mechanical fatigue (TMF)	Blades of medium- and high-pressure turbine
Movable object in electromagnetic fields	Cold working, LCF, HCF, VHCF	Armature of the generator and electric engines
Special object	Ionising radiations, very low temperature (cryogenic), stroke burdens	Elements of a nuclear reactor, cryogenic installations, crash test, unexploded ordnance (UXO)

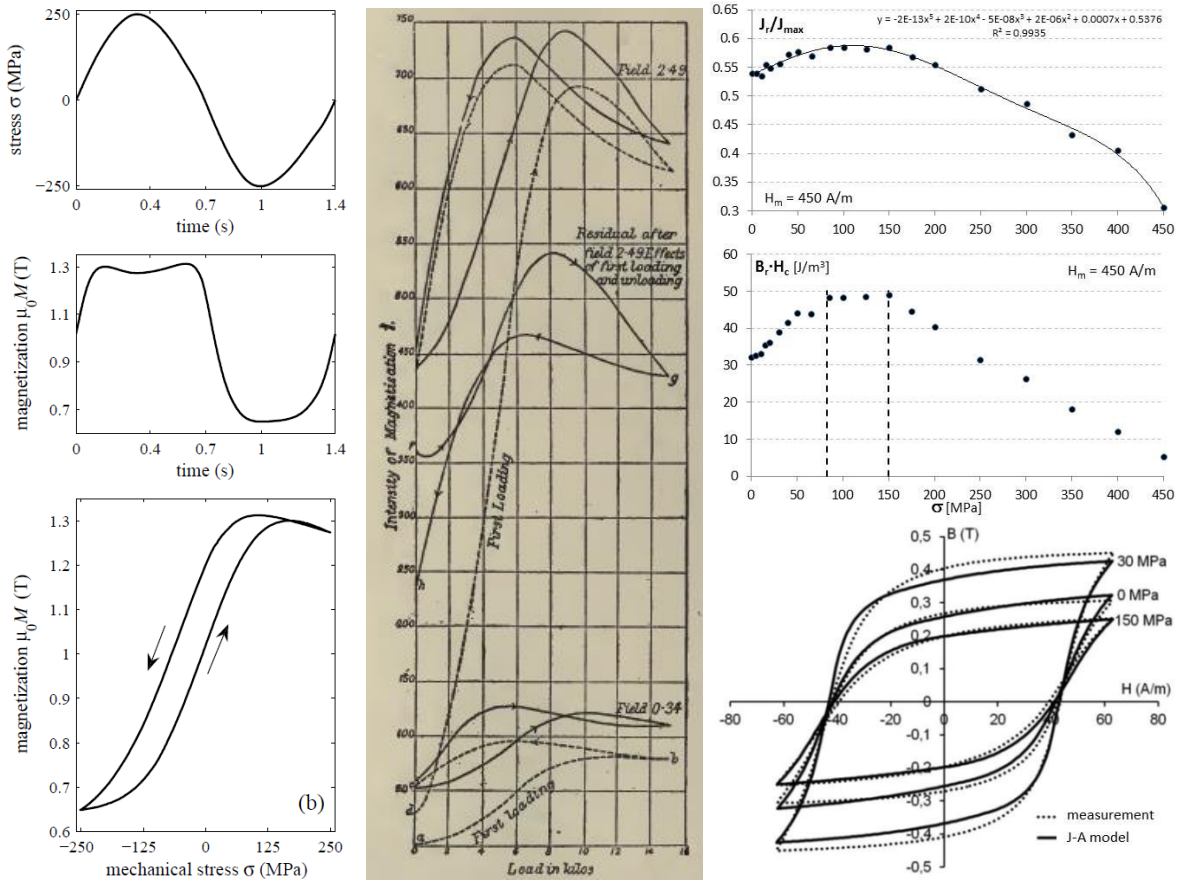
The actual state of material magnetization **M** (of ferromagnetic and paramagnetic elements) can be described by the formula (2)

$$\mathbf{M}(H,T,\sigma,D,t) = (1+k_H)\cdot(1+k_T)\cdot(1+k_\sigma)\cdot(1+k_D)\cdot(1+k_t)\cdot\mathbf{M}_0 \tag{2}$$

in which k_H, k_T, k_σ, k_D, k_t are non-linear coefficients of influence of the external magnetic field **H**, material temperature T, stress tensor σ, change of microstructure properties D (inducted by fatigue, damage or/and phase transformation) and operating time t on the change of initial magnetization $\mathbf{M}_0$ of the material. The change of the material magnetization **M** triggers the change of the magnetic induction **B** in material and it is distribution $\mathbf{B_a}$(x,y,z) above the surface of the examined element. Value of the coefficients copying magnetic and magneto-mechanical characteristics of material can be appointed for given material with experimental method, Figure 3.

Formula (2) is a theoretical base for all active and passive magnetic observers which are used in NDE&SHM applications. For active magnetic observer (i.e. eddy current method, Barkhausen noise method, magnetic flux leakage method) external magnetic field is an know extortion and the k_H coefficient is changeable. For passive magnetic observer (i.e. MMM method) external magnetic field has a quasi-permanent value and its components depend on the location of the monitoring object with regard to magnetic field of Earth [17]: k_H is free-changeable for motionless objects and dependent on the momentary putting for the movable objects. In the general case:

- the passive magnetic observer uses the weak magnetic field for the identification of the material health, and
- k_H has two components: k_{HE} which described influence of geomagnetic field (DC components) and k_{HA} which described influence of artificial field or momentary putting of object (AC components).



a) b) c)

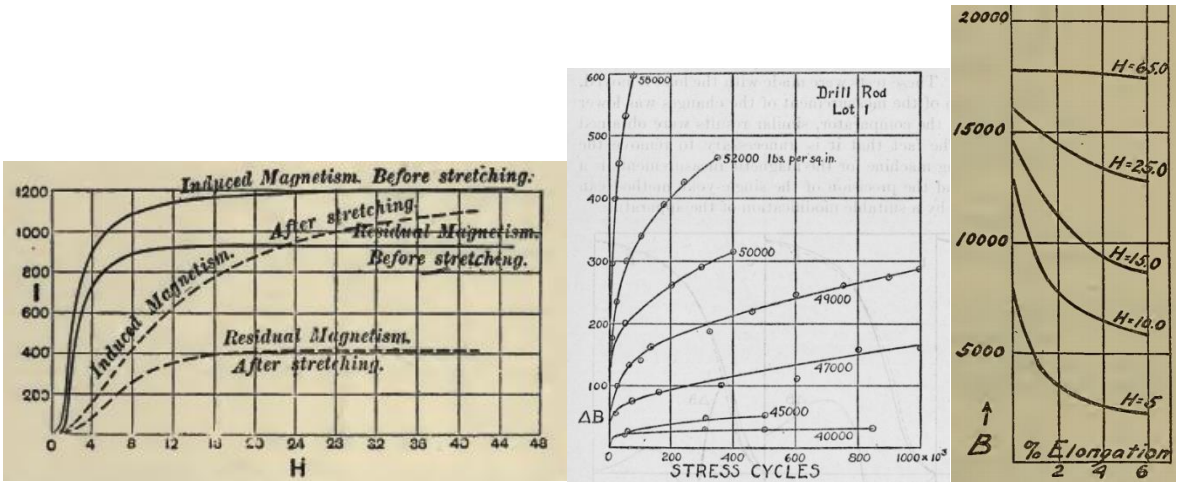
Figure 3: Showing: a) Villari effect – stress inducted magnetization in low carbon steel ($R_{p0.2}$ = 390 MPa, static magnetic field H = 800 A/m) [18]; b) first loading effect – change of magnetizing material after unloading it (CGS units) [19]; c) influence of tension level and H_m on some magnetic parameters of a frames made from low carbon steel ($\sigma < R_{p0.2}$, closed magnetic circuit)

The constitutive law (1) and formula (2) can be saved in the form

$$\mathbf{B}\left(H,T,\sigma,D,t\right) = \mathbf{B}_{DC} + \mathbf{B}_{AC} \cong \mathbf{B}_{ind}(\mathbf{H}) + \mathbf{B}_{rem} + \Delta\mathbf{B}_T + \Delta\mathbf{B}_\sigma + \Delta\mathbf{B}_D + \Delta\mathbf{B}_t \qquad (3)$$

The induced component $\mathbf{B}_{ind}$ is proportional to, and parallel to the outside magnetic field **H**. Remenence (residual) component $\mathbf{B}_{rem}$ is equal zero only for annealed or demagnetised material. In other cases it copies the unknown history of the material used – vector $\mathbf{B}_{rem}$ can accept the any location with regard to the outside magnetic field. The simultaneous polarization of material through the DC and AC components of the magnetic field supports magnetizing it, Figure 4.a).

Changes of material magnetizing, resulting from lattice-spin coupling (L-S) in the atomic scale, distribution of residual stress in the atomic, micro and macro scale and magneto-mechanical effects (reversible and irreversible) in the macroscopic scale, enable the detection 1st phase of the damage [8]. Zones RSC of local residual stress concentration, plastic, material anisotropy (mechanical and magnetic) and dislocation concentration are potential place of cracking nucleation and local magnetic anomaly (pinning magnetic domain) [8, 10, 18-25]. Influence of the local plastic strain of material is the best visible in the weak magnetic field, Figure 4.b) and 4.c). The passive magnetic observer is favoured by authors for NDE&SHM of ferromagnetic and metastable paramagnetic steels.



a) b) c)

Figure 4: Influence of: a) material stretching on change of inducted and residual magnetism; cyclical loads b) and plastic strains c) on changes of material magnetizing [4, 19, 26] (CGS units)

2 COLD WORKING

The operating temperature of diagnosing objects (in this article) does not exceed 30% of the melting point of material thus cold working is a dominating fatigue process of the microstructure. In theoretical considerations, the Hall-Petch and the Bailey-Hirsch relations (4) between microstructure and mechanical parameters is given.

$$\sigma_y \cong \sigma_f(T) + \frac{k_{HP}}{\sqrt{d}}$$
$$\sigma_y(after\ \varepsilon_p) = \sigma_0 + \tau_i \cong \sigma_0 + \alpha G b\sqrt{\rho_d} \qquad (4)$$

where: σ_f – the friction Peierls-Nabarro stress required to move a dislocation in a single crystal, T – material temperature, k_{HP} – material-dependent Hall-Petch constant which represents the difficulty required to unlock or generate dislocations in neighbouring grains, d – the grain diameter, σ_0 – the lattice friction, τ_i – the shear internal stresses, α – constant, G – the shear modulus, b – the crystal lattice parameter (base length of cubic unit cell), ρ_d – the dislocation density [24].

Typical values for carbon steels are: $\alpha \cong 0{,}4$, $b = 0.286$ nm, $d = 10^{-4}$ - 10^{-6} m, $G = 80$ GPa, $k_{HP} = 0.74$ MPa$\sqrt{\text{m}}$, $\sigma_f = 70$ MPa, $\sigma_0 = 100$ MPa [24].

The residual 'life' of material ζ (relative residual time to element break off) is given by local level of dislocation density (5) and gradient of the magnetic anomaly [10]

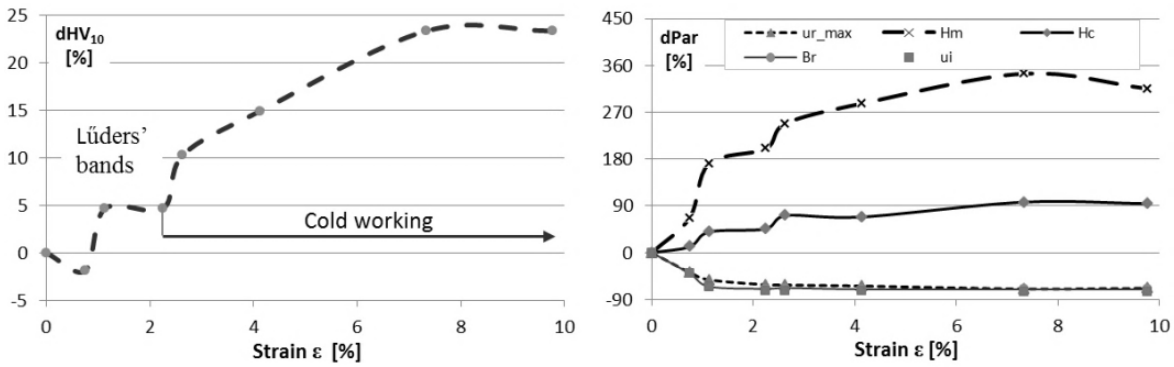
$$\zeta = 1 - \frac{\sqrt{\rho_d} - \sqrt{\rho_{d0}}}{\sqrt{\rho_{dmax}} - \sqrt{\rho_{d0}}} \qquad (5)$$

where: ρ_{d0} – the dislocation density for well-annealed materials, ρ_{dmax} – the dislocation density for ductile strength. Typical values for carbon steels are $\rho_{d0} = 10^{-10}$ m^{-2}, $\rho_{dmax} \cong 10^{-15}$ m^{-2}.

The microstructure parameters of steel (i.e. the grain diameter, the dislocation density, the lattice parameters and the internal stresses) influences on magnetic and magneto-mechanical parameters, Figure 4 and relation (6)

$$H_c \propto \{\sqrt{\rho_d},\ d^{-1}\} \rightarrow \{L_i^{-1},\ \sigma_r\}$$
$$B_r, \mu_{rmax} \propto \{\rho_d^{-1}, d\}$$
$$\mu_i \propto \{L_i^2, \sigma_r^{-1}\} \qquad (6)$$

where H_c – the coercive force; B_r – the remanence; μ_{rmax} – the maximum magnetic permeability; μ_i – the initial magnetic permeability; σ_r – the magnitude of unidirectional internal stress which represents the irregularly fluctuating magneto-elastic energy distribution, L_i – the periodic distance between internal stress centre [24].



a) b)

Figure 4: Influence of cold working low-carbon steel with 0,17% C and ε_{max}=25% on: a) hardness; b) magnetic parameters dPar = (Par(ε) - Par(ε = 0)/Par(ε = 0), $H_m = H(\mu_{rmax})$) [21]

3 EXPERIMENTAL RESULTS

3.1 Turbine blades

The blades of low-pressure turbine are an example of diagnosing the object being located only in the Earth's magnetic field [12]. Quasi-static stretching and cyclical torque and bending are main loading the blades in the changeable weak magnetic field. The fatigue problem is regarding low cycle fatigue (LCF), high cycle fatigue (HCF) and very high cycle fatigue (VHCF) issues with strong influence of erosion, Figure 6.

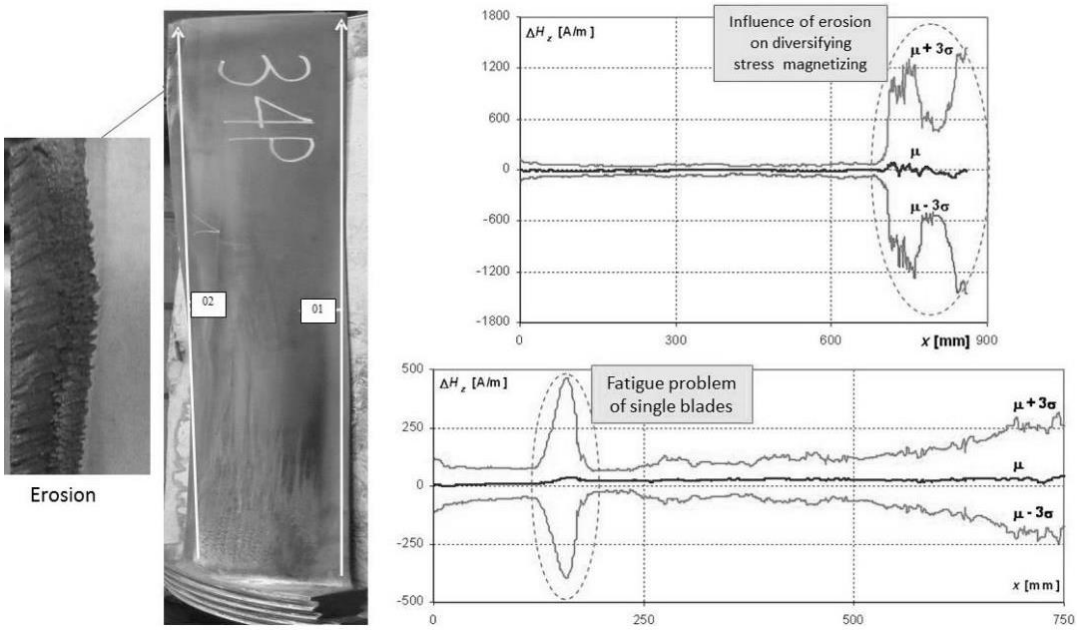
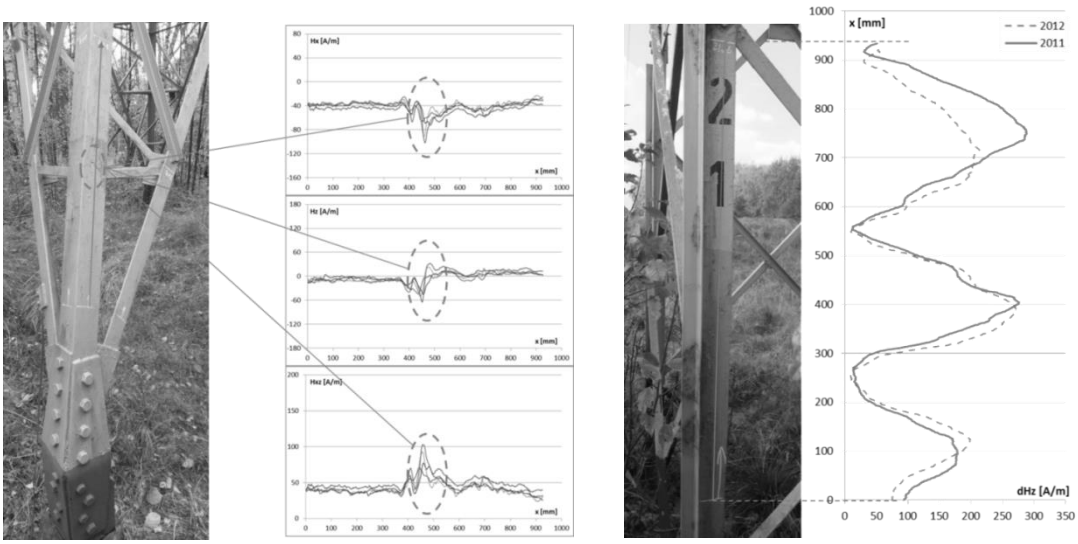


Figure 6. Detection of fatigue problem (copied by the magnetic anomaly in nodal line) before the crack of ND37 turbine blade (statistical analysis with using the method '2-2-3 sigma') [1]

3.1. Electricity pylons of high voltage line

Electricity pylons of HV line are examples of supporting structures being located in weak quasi-DC magnetic field of the Earth, $\mathbf{B}_E$ [17] and alternating electromagnetic fields of HV line, $\mathbf{B}_{50Hz}(t)$. Quasi-static stretching and compressing are main loading of arterial pylons. The strong pylons are also bending and torsion during normal working. The fatigue problem is regarding LCF issues with influence of work hardening phenomena, **H**eat **A**ffecting **Z**one (HAZ) and corrosion, Figure 7.



a) b)

Figure 7: Showing: a) diagnosing of the kerb of the pylon B ON+2.5 using MMM method - the magnetic anomaly is copying the condition of stresses in the welding joint (observation through material of the kerb); b) monitoring applied and residual stresses of the pylon BPiz using the MMM method (the pylon was reinforcement by welding try squares on in 2010, tension corrosion and residual stresses are visible in the Heat Affecting Zones) [27]

4 CONCLUSION

Blades of low-pressure steam turbine and high voltage pylons are made with ferromagnetic steel therefore magnetic methods for NDE and SHM are possible.

The detection of magnetic anomalies (i.e. open crack, zone of residual stress) does not require the knowledge of material features. The quantitative analysis of diagnostic symptoms and prognosis health of objects requires the input data about: geometry of the examined object, initial magnetic and magneto-mechanical properties of its material and expected processes of this one damage.

The passive magnetic observer (measuring data from a vector magnetometer and numerical analysis) of structural health assessment was verified and the potential for reliable diagnosis of the 1st and 2nd phase damage of ferromagnetic material was confirmed.

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