QUANTITATIVE EVALUATION OF BI-AXIAL STRESS IN STEELS: INVERSE PROBLEM SOLUTION

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The report gives up to the quantitative non-destructive evaluation (by the example of magnetic technique) of residual and applied bi-axial stress in steels by considering the problem as unambiguously inverse. That means that the direct mapping of bi-axial stress values from bi-axial measured data using simple calibration procedure is not valid any more. The last problem statement is based on the factual uncertainties of stress values prediction due to the unpredictable influence on measurement results of usually unknown steel treatment prehistory including heat treatment, plastic deformation, surface condition, as well as self- influence of stress tensor components. These conditions are typical for inverse problem methodology. One of the additional disadvantage of conventional approaches consists in the assumption that the main restrictions known for stress and deformation values, like relations between deviator and spherical stress tensor parts are baselessly spread to the similar components of measured magnetic parameters values.

It is important to note that high residual stress level in plastic steel itself does not cause failure while it accelerates metal degradation due to maintenance conditions giving rise to stress-corrosion, fatigue and creep damage, embrittlement, deformation aging, increase in brittle temperature, exhaustion of plasticity margin, etc.

Unfortunately the contemporary non destructive testing (NDT) methods do not provide quick and reliable evaluation of stress distribution in real design. This niche is usually filled by numerical calculation techniques, which use the NDT measurement of thickness, hardness, presence of defects like pores, cracks, geometrical deflections, etc as primary data for calculus. These techniques are usually unable to evaluate stress in stress concentration zones as most dangerous to initiate failure. Thus they can not provide for life time prediction being main purpose for stress evaluation.

The lack of reliable techniques is the reason for lack of standards for stress measurement. Only one international standard is known which regulates the neutron diffraction method [1], and six USA ASTM standards, namely [2] - for hole drilling, [3,4] - for x-ray diffraction, [5,6] – for ultrasonic attenuation methods, and [7] - qualitative method for evaluation of circumferential stress in pipes. Although these techniques are less useful for routine measurements, their importance is evident like reference one for other techniques like UT, magnetic, electro potential, optical, thermal, etc. Unfortunately unique Russian standard ГОСТ РФ 52330-2005 inconsistently reduces the problem of stress measurement to the case of concentration zone detection. Even this wrong conclusion does not sustained by any reliable technique.

A quantity of applications are claimed for stress evaluation in pipe lines, civil constructions, railway, pressure vessels, metallurgy and machine building [8-10]. The present article is the elaboration of biaxial stress quantitative measurement with the help of Barkhausen noise (BN), the last appears to have many advantages, and does not restricts the stated technique application for other NDT methods. The application of the BN technique last years is penetrating quickly in different industrial fields. Several examples below give the notion of these activities: thermal damage in aerospace gears, shot peening techniques, residual stresses after machining, navy structural components surface integrity in aerospace industry, stress corrosion prediction.

As mentioned, despite of high sensitivity of different physical parameters, like magnetic, acoustic, eddy current, electropotential, etc. to the stress variations, the measurement uncertainty, caused by concomitant dependence of these physical parameters upon other material properties, stays as the main restriction to the application of NDT techniques for stress measurement. To recover stress from physical parameters measurements, those concomitant relationships between informative and influencing parameter respectively should be successively taken into consideration as a priori conditions. The recovery procedure is unable to exclude all influences, thus attracting attention to the most critical, one of them being uncertainty due to bi-axial condition, usually important in many applications.

Traditionally the stress calibration procedure for bi-axial stress condition is reduced to that for uni-axial stress state. From very basic considerations it clear that this assumption is not correct. Several attempts have been made to extract the specific properties of bi-axial stress condition from bi-axial calibration, but in fact only the property like stress deviator, not stress components themselves, can be acquired in the result [11-13]. The main disadvantage of conventional approaches consists in the assumption that the main restrictions known for stress and deformation values, like relations between deviator and spherical stress tensor parts are baselessly spread to the similar components of measured magnetic parameters values. This yields additional uncertainty to the bi-axial stress measurement via magnetic parameters. Recently we introduced some new opportunities to improve the selectivity of BN technique [14,15]. They have been mainly integrated in the new instrument "Introscan", developed and produced by R&D "Diagnostics". The goal was to make a step from stress qualitative assessment to stress measurement. This step includes the angular and amplitude scanning of driving magnetic field and its feed back control to provide stabilization of magnetic flux density in the material under test. At the same time it makes possible to use alternative parameters of BN like "field of start" and so called "gutter" to improve measurement facilities of BN instruments and to facilitate stress measurement in the material with small microstructure deviations. Those improvements helped to overcome many restrictions on the way for stress measurement at un-iaxial condition.

In the present elaboration the problem of bi-axial stress assessment is formulated as indirect, while the measured data like BN values – as incomplete and noisy. The „incomplete and noisy„ means that: a) direct transformation matrix *O* is unknown or known but underestimated, can't be inverted and the inverse operator O^{-1} is unknown; b) the noise in general is unknown and is not additive. The recovering of the two principal stress values from measured data is then can be done by the following variation equation:

$$(\tilde{\sigma}_1,\tilde{\sigma}_2)=\inf\left\{\left\|O(\tilde{\sigma}_1,\tilde{\sigma}_2,T+\phi_i)+\eta-p^m(\phi_i)\right\|^2+\alpha B(\tilde{\sigma}_1,\tilde{\sigma}_2):(\tilde{\sigma}_1,\tilde{\sigma}_2)\in R^2\right\}, \qquad (1)$$

with $p^m(\phi)p$ – experimentally measured principal stress values in the time or spatial domain, $O(\tilde{\sigma}_1,\tilde{\sigma}_2)$ - direct operator: calculated value of the measured BN signal over principal stress values due to the selected model (calibration characteristic in the absence of influencing parameters like microstructure, other stress tensor components, residual plastic deformation, different stress heterogeneity, noise, etc.; $(\tilde{\sigma}_1,\tilde{\sigma}_2)$- is the pair of principal stresses; ϕ– variation parameter during data acquisition process, e.g. rotation angle of the sensor or its coordinate, etc.; η - noise accompanying the measurements, α - regularization parameter; $B(\tilde{\sigma}_1,\tilde{\sigma}_2)$ - functional describing the a priori information (AI) about a spatial distribution of principal stresses; *R* – definitional domain of the principal stress values.

In common case of known principal stress directions (e.g. in bridge constructions, pipes, pressure vessels and so on) the data acquisition is reasonable to provide by variation of magnetic excitation field direction, ϕ_i , and measuring the BN intensity signal, $p^m(\phi_i)$. In this case the AI will involve the penalized support of the well known rule for biaxial stress state: the sums of each pair of self-perpendicular normal stress components are invariant under the direction in a biaxial plain:

$$\sigma(\phi_i)+\sigma(\phi_i+90^0)=\sigma_1+\sigma_2 \qquad (2)$$

Subject to this rule the equation (1) can be finally written in the form:

$$(\tilde{\sigma}_1,\tilde{\sigma}_2)=\inf\left\{\begin{array}{l}\left\|p^c(\tilde{\sigma}_1,\tilde{\sigma}_2,\phi_i)-p^m(\phi_i)\right\|^2+\\ \alpha\left\|(\tilde{\sigma}_1+\tilde{\sigma}_2)-\left[\sigma(\phi_i)+\sigma(\phi_i+90^0)\right]\right\|^2:\\ (\tilde{\sigma}_1,\tilde{\sigma}_2)\in R^2\end{array}\right\} \quad (3)$$

where $p^c(\tilde{\sigma}_1,\tilde{\sigma}_2,\phi_i)$ - the calibration angle dependence of the BN signal.

The illustration for the f-la (3) application to the pair principal stress values $(\tilde{\sigma}_1,\tilde{\sigma}_2)$ reconstruction given input data in the form of stress angular function, $\sigma(\phi_i)$, under the uni-axial cantilevered bending of the plate 250x40x4 mm from 300M steel after quenching and 3 times tempering is shown in the fig.1. The specimen was subjected to bending deformation to the calculated level of longitudinal normal stress 858MPa. Fig.1b shows the angle dependence (AD) of BN signal, while fig. 1a shows AD of BN signal at zero bending stress. The MPa scale is also shown at the left of BN signal scale. It is seen that the signal (and corresponding stress) increment after bending (difference between diagrams in fig.1a and fig.1b) is very small and does not conforms to large stress variations and the condition of zero stress at transverse (relatively to bending) direction. Estimated values are $\tilde{\sigma}_1=320MPa$, and $\tilde{\sigma}_2=-60MPa$, what is far from reality. The reconstructed diagram due to equation (3) and uni-axial calibration is shown in the fig. 1c. It was assumed that α=0,25. Considering a non zero thickness of the layer of BN sensitivity it looks much more likelihood than the diagram in the fig. 1b. The estimated values of principal stresses on the surface are equal $\tilde{\sigma}_1=625MPa$ and $\tilde{\sigma}_2=-12MPa$.

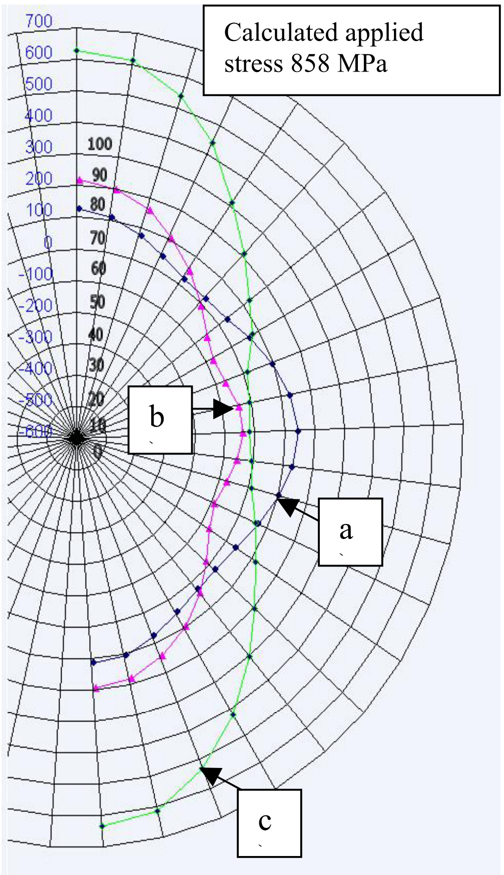

Fig.1. AD of BN signal:
a) – measured at zero bending stress;
б) – measured at bending stress 858 MPa;
в) – reconstructed with the help of equation (4) AD at the surface of the cantilevered beam

The next step was done to enable the uni-axial calibration curve for bi-axial stress reconstruction considering the elastic theory equations for bi-axial stress condition:

$$\sigma_1=E\varepsilon_1+\lambda\sigma_2; \qquad \sigma_2=E\varepsilon_2+\lambda\sigma_1. \qquad (4)$$

From the equation (4) it follows that the stress in any principal direction depends not only upon deformation value in the same direction but also upon the other stress component value respectively. The similar statement is particularly valid with respect to the measured BN signals. To overcome the restriction caused by the self-influence of both principal components, the special type of the inversion tetra-axial diagram was proposed and validated.

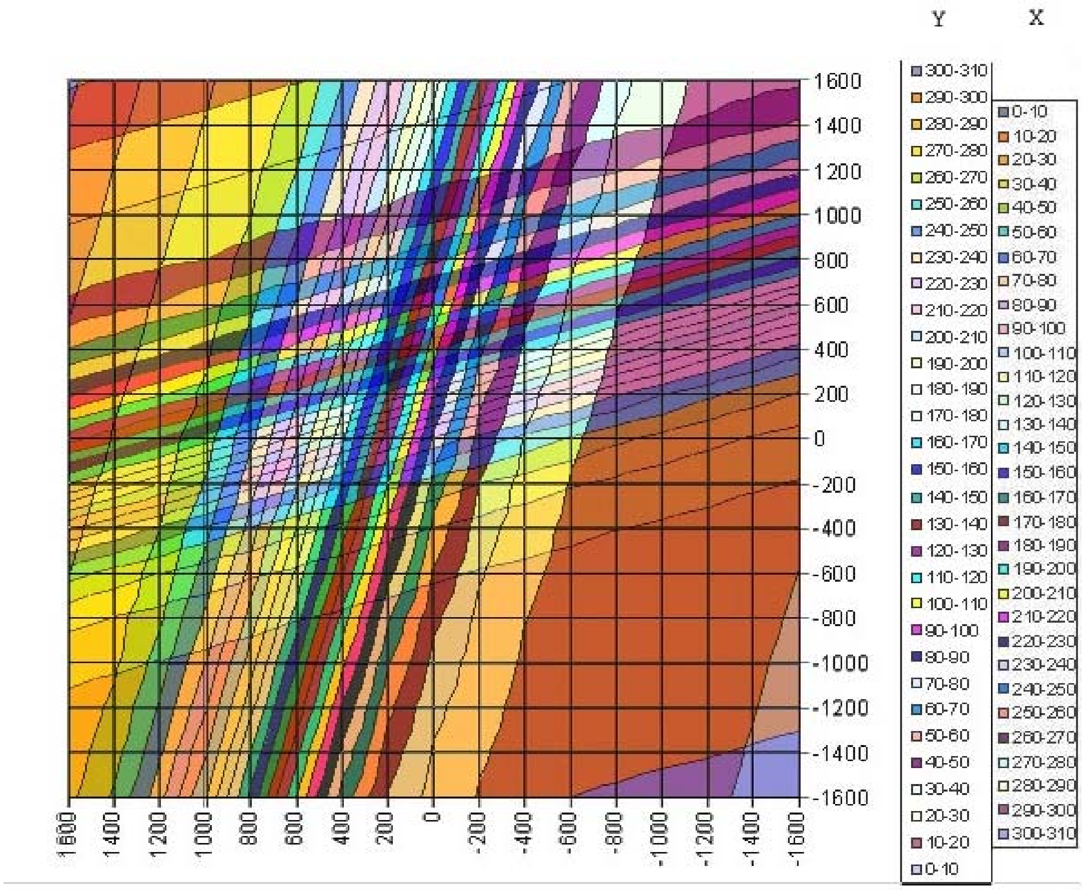

Fig.2. Tetra-axial diagram for low alloy steel used for the reconstruction of bi-axial stress values (x-y axis on the diagram, scaled in MPa) from bi-axial measurement results of Barkhausen noise (two inclined set of lines scaled in BN signal values by two columns on the right of the diagram). This calibration diagram represents the special type of data inversion considering the elastic theory equations (4) for bi-axial stress condition.

The diagram in Fig.2 is obtained considering two main physical patterns of relationship:

- It can be acquired with the uni-axial deformation of plane specimens as it usually implemented for uni-axial case;
- it integrates the uni-axial calibration curve, which is the dependence of BN measurement results via uni-axial stress values reached by tension-compression or bending of the plane specimen. The uni-axial calibration curve for corresponding low alloy steel is shown in the fig.3. The possibility to use uni-axial deformation to calibrate bi-axial stress state is one of the important results of the current elaboration;
- the appropriate way to use tetra-pole diagram with the magnetic parameter values plotted as iso-lines inside the diagram itself;
- the principal stress values are scaled as the bi-axial coordinates at the bi-axial orthogonal coordinates;
- the uni-axial calibration curve for magnetic properties, specifically Barkhausen noise, dependence on stress value variation is usually non linear what is reflected in the non-uniform density of the iso-lines on the tetra-pole diagram;
- the inverse problem solution includes graphical reconstruction procedure by moving from non uniform set of bi-axial magnetic values to bi-axial stress values, plotted on the uniform scale;
- the tetra-pole diagram does not consider a compensation of micro structure or plastic deformation deviations from calibration conditions but it is clear that, while those

deviations could take place, they would displace the geometrical centre of the magnetic properties set center from the position of stress values coordinates center respectively.

- the equation (4) is integrated in the calculation of the diagram: the two sets of inclined lines are simply the terms of two corresponding transposed matrices, each representing the results of the uni-axial measurements.

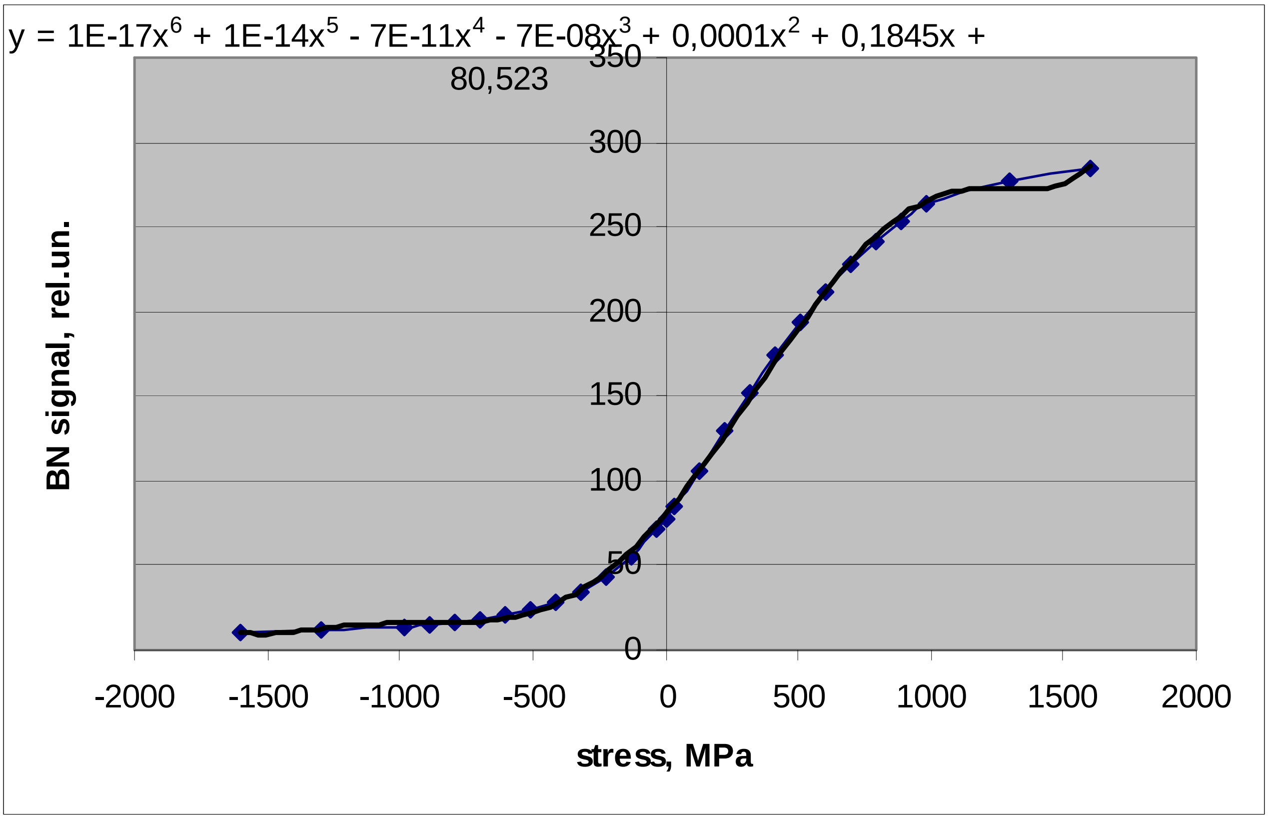

Fig. 3. Uni-axial calibration curve for BN value via bending stress for low alloy high strength steel 30HGSNA. Used for acquiring the diagram in the fig.2.

The non linearity of the BN value via bending stress dependence is transformed into the observed non uniformity of a density of inclined lines in the fig.2: the highest is the sensitivity of BN values to the variation of stress values (fig.3) the higher is the density of iso-BN lines in the fig.2.
The application of the diagram in the fig.2 is quite easy: given the results of the BN measurements in two principal directions (the directions are usually known in the engineering practice) one has to find the cross point of the corresponding incline lines, to project this point to x-y axes and to get in return the stress values in MPa in both principal directions.
Simultaneous solution and data fusion of both discussed inversion opportunities makes it possible to recover principal stress components from angular dependence of BN. The similar mathematical and experimental instruments should be applied to any other NDT bi-axial stress quantitative evaluation method to meet the challenges caused by the uncertainties in stress prediction by non destructive measurement technique.
The proposed technique facilities are integrated in the instrument “INTROSCAN” and special software which supports the reconstruction procedure given experimental data of BN signal acquired during the automatic rotation of the excitation magnetic field vector.

Conclusion

1. The bi-axial stress quantitative evaluation via magnetic measurements is considered as an inverse problem of principal stress tensor components reconstruction from bi-axial magnetic parameters measurements given uni-axial calibration diagram.
2. The uni-axial calibration is available to provide bi-axial stress measurements with magnetic technique if one considers the elastic theory equations for bi-axial stress condition, which together with uni-axial calibration curve can be represented in the form of tetra-axial diagrams like a specific graphical way for inverse problem solution.

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