1.2.13. 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 the metal degradation damage due to stress-corrosion, fatigue, creep, embrittlement, etc. A quantity of applications are claimed for stress detection in pipe lines, civil constructions, railway, pressure vessels, metallurgy and machine building. 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.

In the present elaboration the problem of 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:

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

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; $B\left(\tilde{\sigma}_1, \tilde{\sigma}_2\right)$ – 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:

$$\sigma\left(\phi_i\right)+\sigma\left(\phi_i+90^0\right)=\sigma_1+\sigma_2 . \tag{2}$$

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

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

where $p^c\left(\tilde{\sigma}_1, \tilde{\sigma}_2, \phi_i\right)$ – 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 $250\times40\times4$ mm from 300 M 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 858 MPa. Figure 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 $\tilde{\sigma}_1 = 320$ MPa, and $\tilde{\sigma}_2 =$ $= -60$ MPa, 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 $\alpha = 0.25$. 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 $\tilde{\sigma}_1 = 625$ MPa and $\tilde{\sigma}_2 = -12$ MPa.

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:

$$\sigma_1 = E\varepsilon_1 + \lambda\sigma_2 ; \quad \sigma_2 = E\varepsilon_2 + \lambda\sigma_1 . \tag{4}$$

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. 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 stress quantitative evaluation method to meet the challenges caused by the uncertainties in stress prediction by indirect 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.

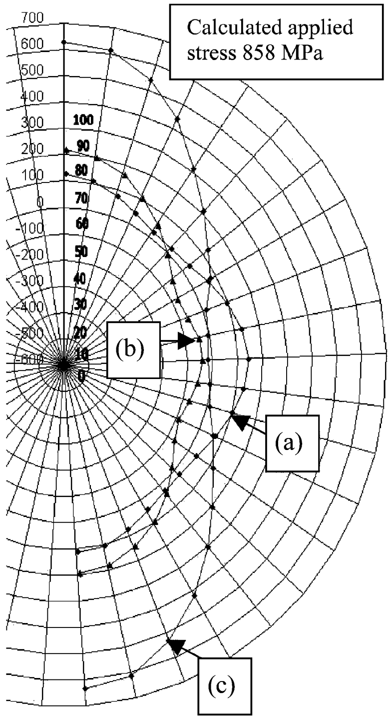

Fig. 1. AD of BN signal:
(a) – measured at zero bending stress;
(b) – measured at bending stress 858 MPa;
(c) – reconstructed with the help of equation (4) AD at the surface of the cantilevered beam