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BI-AXIAL STRESS QUANTITATIVE EVALUATION WITH BARKHAUSEN NOISE: THE PAST AND PERSPECTIVES.

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Abstract

Residual and applied stress evaluation in the design and exploited structures is one of the key problem which gives the opportunity to predict remaining life, optimize engineering process and avoid failure. The present article is the elaboration of biaxial stress quantitative investigation with the help of Barkhausen noise (BN), the last appears to have many advantages. 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.

Two specific arrangements for bi-axial experiments by compression-tension and bending respectively have been designed, which provided for accurate simultaneous measurement of deformation values along with magnetic values at the cross-like steel specimens. That gave the opportunity to plot different combinations of principal BN components over deviator and spherical stress tensor parts, their relations and von Mises deformations respectively. This helped to determine important patterns for the relations between these properties, which can be successfully used for the interpretation of bi-axial stress measurements in practical applications.

Keywords: stress evaluation, Barkhausen noise

1. Introduction

Residual and applied stress evaluation in the design and exploited structures is one of the key problem which gives the opportunity to predict remaining life, optimize engineering process and avoid failure. The present article is the elaboration of biaxial stress quantitative investigation with the help of Barkhausen noise (BN), the last appears to have many advantages. 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

A quantity of applications are claimed also for stress detection in pipe lines, civil constructions, railway, pressure vessels, metallurgy. But minimizing uncertainties in stress prediction is still on the agenda. A couple of new opportunities on this way are shown below. 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 [1-3]. This yields additional uncertainty to the bi-axial stress measurement via magnetic parameters. Limitations of the BN technique are also related to the testing materials, which are steels and cast iron only, limited penetration depth, influence on the measurement results by microstructure, surface decarburization, bulk chemical content deviations and surface condition.

Recently we introduced some new opportunities to improve the selectivity of BN technique [4-6]. 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 in uni-axial condition.

But measurement of a bi-axial stress, which is much more frequently appears in practice, is still very uncertain. The article shows serious reasons for such uncertainty and proposes some ways to avoid them. The theoretical analysis of the problem returns us to the view on it as a principal inverse problem. Thus the article shows the way to apply Bayesian approach to restore principal stresses from BN measurement. It is shown that basically this approach assumes using bi-axial calibration results. Therefore two specific arrangements for bi-axial experiments by compression-tension and bending respectively have been designed, which provided for accurate simultaneous measurement of deformation values along with magnetic values at the cross-like steel specimens. This gave the opportunity to plot different combinations of principal BN components over deviator and spherical stress tensor parts, their relations and von Mises deformations respectively. In its turn, this helped to determine important patterns for the relations between these properties, which can be successfully used for the interpretation of bi-axial stress measurements in practical applications.

2. Bi-axial stress measurement as an inverse problem

From information point of view all measurements, like stress, could be characterized as „indirect„ while the output data – as incomplete and noisy[7,8]. The transformation of the input data supposing the noise is additive is described by the following operation equation:

$$p^m(\phi_i) = O(\tilde{\sigma}_1, \tilde{\sigma}_2, T + \phi_i) + \eta\,, \qquad (1)$$

with $p^m(\phi)p$ – experimentally measured principal stress values in the time or spatial domain, $O(\tilde{\sigma}_1, \tilde{\sigma}_2, T)$ - direct operator: calculated value of the measured BN signal over principal stress values due to the selected model; $(\tilde{\sigma}_1, \tilde{\sigma}_2)$- is the pair of principal stresses; T – spatial displacement of principal stresses in the signal measurement domain; ϕ – variational parameter during data acquisition process, e.g. rotation angle of the sensor or its coordinate, etc.; η - noise accompanying the measurements.

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. However, while the classical solution of the eq. (1) is mostly doesn’t exist the general solution called pseudo-solution is attainable after filtering by available filter, the simplest one is least squares. Within biaxial stress state assumption it recovers for two principal stresses the pseudo-solution from the following variational equation:

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

where α - regularization parameter; $B(\tilde{\sigma}_1,\tilde{\sigma}_2,T)$ - functional describing the a priori information (AI) about a spatial distribution of principal stresses; R – definitional domain of the principal stress values;

Matrix $O(\tilde{\sigma}_1,\tilde{\sigma}_2,T+\phi_i)$ can be considered as some calibration characteristic in the absence of influencing parameters like microstructure, other stress tensor components, residual plastic deformation, different stress heterogeneity, etc. To apply formula (2) for the data analysis one has to pass through the informal steps which in short are pointed below:

1. Description of the problem stressing on the definition of:
   a) the process model or the operator $O(\tilde{\sigma}_1,\tilde{\sigma}_2,T+\phi_i)$, called also instrumental function
   b) prior pdf $B(\tilde{\sigma}_1,\tilde{\sigma}_2,T)$ and a priori knowledge about the norm space R^n
   c) data acquisition arrangement
2. Estimation of the coefficient α like a measure of our belief either in the measured data or in the prior information
3. Data acquisition and grouping procedure
4. Estimation of the noise characteristics (optional)
5. Minimization procedure to calculate the most probable solution for the unknown material properties $(\tilde{\sigma}_1,\tilde{\sigma}_2)$ given output data, prior and instrumental function.

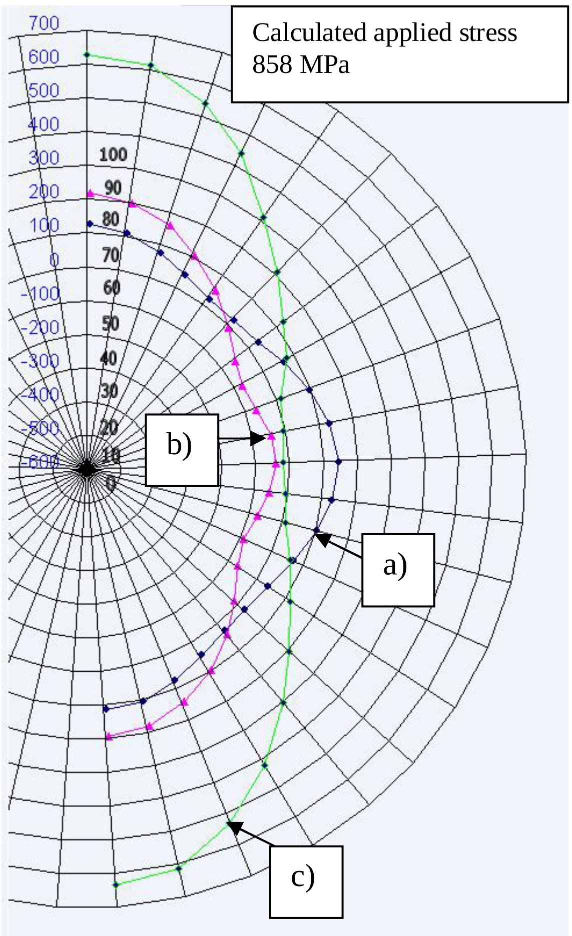

Fig.1. AD of BN signal:
a) – measured at zero bending stress;
б) – measured at bending stress 858 MPa;
в) – reconstructed with the help of equation (4) AD at the surface of the cantilevered beam

Frequently the principal stress directions are known. This takes place e.g. in bridge constructions, pipes, pressure vessels and so on. Data acquisition is reasonable to provide by variation magnetic excitation field direction, ϕ_i , and measuring e.g. 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:

MPa

$$\sigma(\phi_i)+\sigma(\phi_i+90^0)=\sigma_1+\sigma_2 \quad (3)$$

Subject to this rule the equation (2) can be written in the form:

$$(\tilde{\sigma}_1,\tilde{\sigma}_2)=\inf\left\{\begin{array}{l}\left\|p^c(\tilde{\sigma}_1,\tilde{\sigma}_2,\phi_i)-p^m(\phi_i)\right\|^2+\\ \alpha\left\|(\tilde{\sigma}_1+\tilde{\sigma}_2)-\left[\sigma(\phi_i)+\sigma(\phi_i+90^0)\right]\right\|^2:\\ (\tilde{\sigma}_1,\tilde{\sigma}_2)\in R^2\end{array}\right\} \quad (4)$$

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

3. Simulating the problem of principal stress values reconstruction from BN measurement

We illustrate the stress inverse problem application by reconstructing the principal stresses, ($\tilde{\sigma}_1, \tilde{\sigma}_2$), and 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. The result is clear from fig.1. The specimen was subjected to bending deformation to the calculated level of longitudinal normal stress 858MPa. Fig.1b shows the 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 (4) and uni axial calibration, made previously[], 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 $\tilde{\sigma}_2 = -12MPa$.

4. Search for the parameters characterizing the bi-axial stress state

The main problem to solve the equation (2) is to propose the adequate procedure to develop the calibration characteristic for BN dependence via stress principal components. The primitive analysis shows that there is no chance to use uni-axial deformation experiments to acquire a bi-axial stress diagram. This statement comes from taking into account the elastic theory equations for bi-axial stress condition:

$$\sigma_1 = E\varepsilon_1 + \lambda\sigma_2 ; \qquad \sigma_2 = E\varepsilon_2 + \lambda\sigma_1 . \tag{5}$$

From the equation (5) 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 respectively. The similar statement is particularly valid with respect to the measured BN signals. Thus it is clear that calibration characteristics for bi-axial state should provide for bi-axial tests.

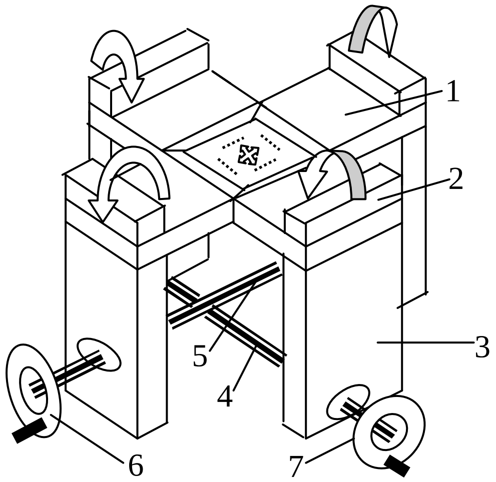

Fig. 2. Laboratory device for the cross-like specimen 1 testing by bi-axial bending: 2 – clamp; 3 – arm; 4,5 – driving screws; 6 – driving lever.

The sketch of the developed device for bi-axial bending is shown in the fig.2. It has at least three advantages over commonly used tension-compression machines: the simplicity of specimen centering, symmetry of two-sided deformation and fixed deformation while bending in the transverse direction. The disadvantage is the special requirements to the specimen shape, which of the cross-like specimen's shape was done by simulating it under the condition of maximal uniformity of stress on the surface. The real deformation values were measured by four stress sensors shown with dotted lines.

All measurements have been done with the help of BN analyzer "Introscan" at the magnetization frequency 30 Hz and analyzing frequency range (5-30) kHz.

At all diagrams below to estimate real deformations one should multiply the plotted values at x-axis by 10^{-6}. The objective of the experimental session was the search for BN parameters approximating bi-axial stresses linearly and minimizing influencing factors described above.

Previously it was discussed that the above mentioned properties [14] should belong to the magnetic parameter similar to the stress deviator, but named "signal deviator": the difference of the two signal values measured in both principal directions: $p(\sigma_1) - p(\sigma_2)$. Fig.3 shows its dependence over both principal stress components respectively. The accuracy

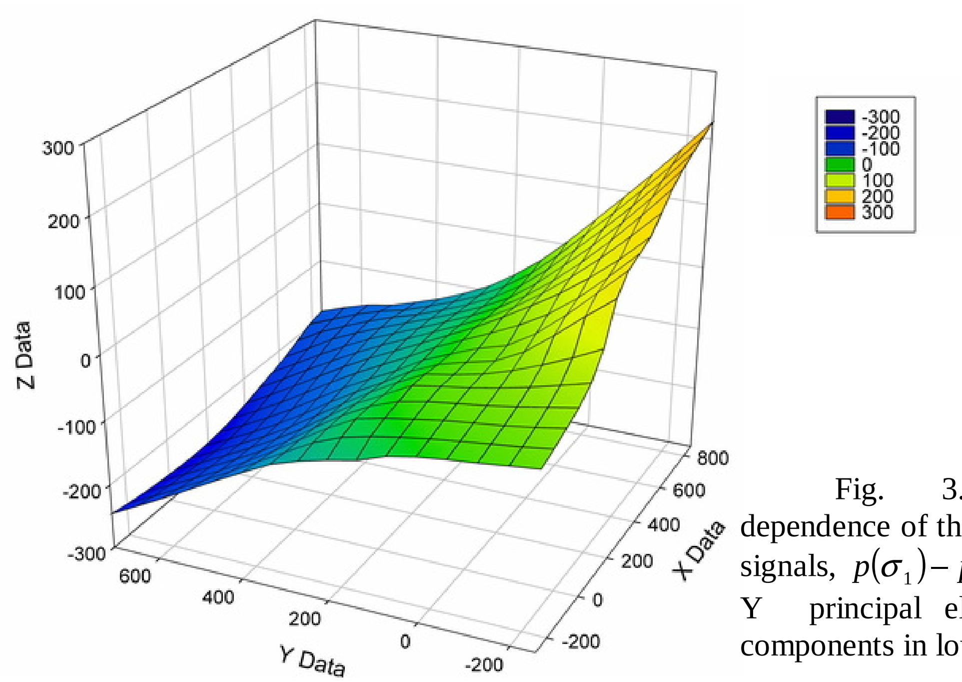

Fig. 3. Approximated dependence of the difference of BN signals, $p(\sigma_1) - p(\sigma_2)$, over X and Y principal elastic deformation components in low carbon steel.

of those experiments was not so good, thus we can only watch the tendency in comparison with well known non linear dependence of BN signal for a low carbon steel.

As the Mises stress characterizes a shear stress component, it is also of interest the behavior of the signal characteristic named "Mises BN signal": $p_M = \sqrt{p_1^2 + p_2^2 - p_1 \cdot p_2}$. The experiments were done with high strength alloy VNS-2 with the yield strength higher that

2000 MPa. The results are shown in the fig. 4. The saddle-shaped part of left surface corresponds approximately to the shear stress component minimum (spherical part maximum) what is in agreement with the assumption about insignificant contribution of a spherical stress component to the magnetic signal.

Conclusion

(1) From information point the quantitative non destructive evaluation of stress values belongs to the problems with strong uncertainty due to the dependence of used physical parameters also upon microstructure, residual strain, surface conditions. Thus the optimal information processing approach should be applied to extract unknown information, the Bayesian inverse theory with a priory knowledge consideration being one of the mostly attractive.

(2) The quantitative non destructive evaluation of stress values is possible only if the calibration procedure assumes bi-axial experiments. The corresponding simple laboratory device and technique are proposed to implement this kind of experiments with sufficient accuracy.

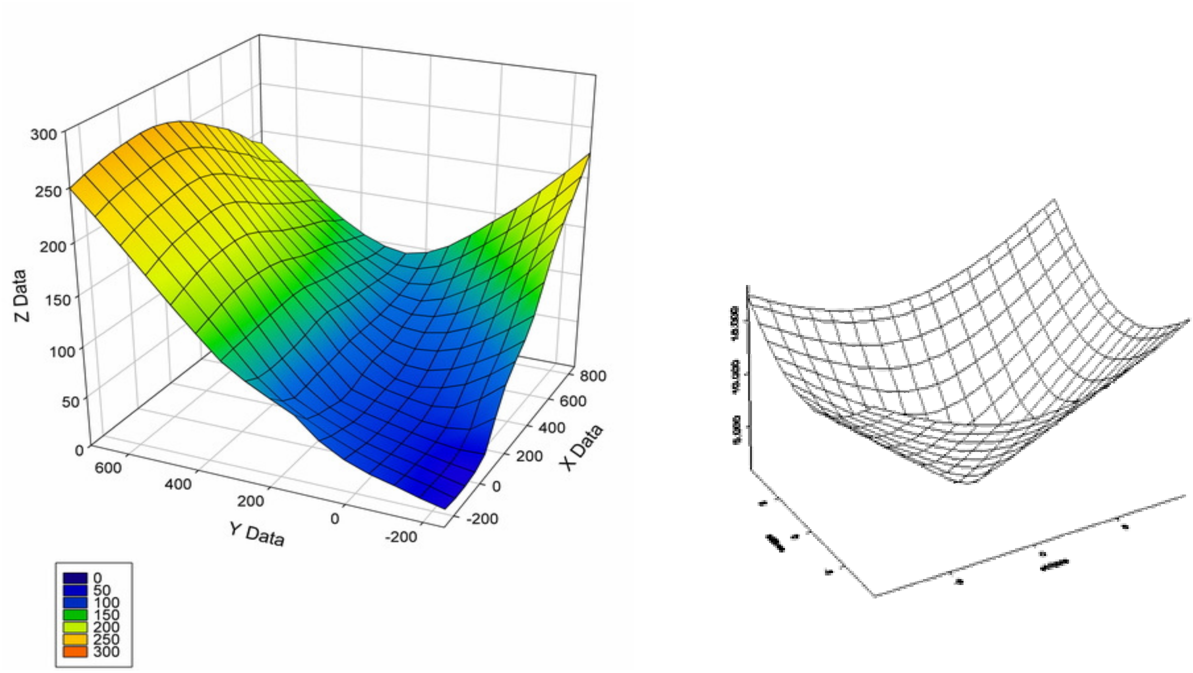

Fig.4. The surface $p_M(\varepsilon_1, \varepsilon_2)$ for the "Mises BN signal" (left) for high strength alloy VNS-2 acquired from bi-axial stress tests. At right the regular Mises surface for the deformation in two directions is shown.

References

[1] C.S.Schneider, P.Y.Cannell and K.T.Watts. Magnetoelasticity for large stresses. *IEEE Transactions on Magnetics*. Vol.28, 1992, p.2626.

[2] M.J.Sablik. Modeling the Effects of Biaxial Stress on Magnetic Properties of Steels with Application to Biaxial Stress NDE. *Nondestructive Testing and Evaluation*. Vol.12, No. 2, 1995, pp.87-102.

[3] Belle A, Langman RA. Determining absolute stresses by a non-destructive magnetic technique, *14th Australasian Conference on the Mechanics of Structures and Materials*, Hobart, 1995, pp.193-199.

[4] V.Vengrinovich and V.Tsukerman. New Potentialities for Stress Measurement by Magnetic Barkhausen Effect. Proc. Of the 8-th ECNDT, CD, Barselona, 2002

[5] Vengrinovich V.L., Vishnevsky A. and Knyazev M., The Principles of Depth Analysis of Surface Hardened Layers by Magnetic Noise Method. J."Research in Nondestructive Evaluation". V.4, No.1, (1992), 19-27

[6] V.Vengrinovich, J.Denkevich and V.Tsukerman. New Potentialities for Stress Measurement by Magnetic Barkhausen Effect. J. "NDT World", №1, 2005, pp. 36-39.

[7] A.Zellner. Optimal information processing and Bayes theorem. *American Statistican*, **v.42 N4**, pp.278-284, 1998.

[8] J.Skilling. Probabilistic data analysis: an introductory guide.*Journal of Microscopy*, **v.190,**Pts.1/2, pp.28-36, 1998.