STRESS AND TEXTURE MEASUREMENT USING BARKHAUSEN NOISE AND ANGULAR SCANNING OF DRIVING MAGNETIC FIELD

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Abstract: New instrument Introscan, tetra-pole probe and the technique for fast and easy on-line measurement, plotting and recording of the functions of Barkhausen Noise intensity upon the angle of an excitation magnetic field vector direction, so called Directional Diagrams (DD), are developed. It is shown that DD shape is quantitatively and qualitatively characterizes the anisotropy behavior of a plane stress state and texture for a test material. This technique can be the experimental basis for the plane stress tensor components reconstruction using DD data and the calibration functions, made with the same acquisition system.

Introduction: The in-service assessment of internal stresses is one of the important problem necessary to help in avoiding destruction and life time prediction due to the fact that internal applied and residual stresses together with metal's properties predefine the integrity and safety in a design. General problems, which different Non Destructive Evaluation (NDE) methods, like magnetic, eddy-current, ultrasonic or x-ray, etc. deal with, while evaluating stress condition, are substantially caused by the nature of the measured data, which are usually noisy, fuzzy and shadowed by the effects like microstructure, surface condition, texture, preliminary plastic deformation of the material under test. For all known methods, discussed in [1,9], the influence of those factors on the results of stress measurement is usually dramatic. The problem of eliminating the influence of some disturbing factors on the stress NDE, being applied to Magnetic Barkhausen Effect (MBE), is the focus of the present article, provided that high stress sensitivity of MBE with regard to internal stresses in ferromagnetic material with non zero magnetostriction is generally acknowledged.

MBE-based technique is one of the most perspective methods for NDE transition from stress estimation to in service stress measurement. The reasons are: already mentioned high stress sensitivity, high space resolution of Barkhausen Noise (BN) sensors, their conformity with major shapes and forms of surfaces, insignificance of magneto-elastic hysteresis. Nevertheless, in spite of many innovations, being in the focus of last decade activities in MBE technique, the existing stress measurement accuracy is far from satisfactory.

Besides of the estimate of the construction integrity, improvement of stress NDE precision is motivated by many purposes. Among them: development of easy reproducible and competitive stress gauge [2], which could compete to well known strain gauge; indirect measurement of intrinsic pressure in pressure vessels; development of new MBE-based sensors for load and weight measurement. It is clear that in order to strive for better precision of stress measurement techniques it is necessary to consider the tensor-like nature of stresses, to make efforts for suppressing a concomitant noise and influencing factors, like microstructure and chemical inhomogeneity; to consider the BN attenuation [10], to search for new parameters with improved robustness with regard to noise.

In our later works some elaborations have been demonstrated, directed to the stress measurements with depth resolution [3], providing for temperature stability [4], microstructure statistical analysis, basing on the reconstruction of the probability density distribution function of magnetization micro volumes [5].

The measurement of statistic parameters of BN needs precise and comprehensive instruments. Most of the existing use the effective voltage of BN to characterize its integral intensity in the specimen under uni-directional magnetization. Some other proposals have been announced last time to improve the selective sensitivity to possible material changes like plastic deformation [6]. The new instrument "INTROSCAN" [7] is developed by R&D "Diagnostics" to improve measurement characteristics of the instruments of former generation, having the objective to make the step from stress qualitative assessment to stress measurement. This transition is grounded on multi parameter measurements the facilities for measuring of the parameters of the Domain Walls avalanche-type aftereffect, providing of the "pure" Barkhausen noise measurement independently of the concomitant variations of magnetic characteristics.

In this article we continue the experimental investigation of the new capabilities given by Introscan by means of BN measurement in the operation mode, which is applied magnetic field angle scanning. In its turn this operation mode may be applied in two sub mode versions:

- stabilization of applied magnetic field intensity;
- stabilization of magnetic flux in the magnetic circuit, consisted of sensor's core and test specimen's part.

In both cases the excitation magnetic field vector is subjected to step-wise angle scanning and BN measurement is provided in between two close steps. In the result the so called Directional Diagrams (DD) of BN are displayed, which shape. In the second case the additional affordability to lift off and magnetic properties variations is reached by the instrument.

Results: The benefits, which can be taken from measuring DD of BN were illustrated in [8]. The idea comes out from the tensor behavior of stress components, six independent tensor components being in every point of a loaded article. If a specimen thickness is much less than its width and length, its stress state is considered as plane one. As the BN probe's magnetic circuit creates an excitation magnetic field in the area of a pick up coil location only in a tangential plane, the pick-up coil reacts exclusively to the variation of three plane tensor components: σ_{xx}, σ_{yy} and τ_{xy}. With some concern it is assumed, that three other components: σ_{zz}, σ_{xz} and σ_{yz} do not influence the BN intensity.

The principle of exciting magnetic field vector angle scanning in the surface plane is clear from the chart in the Fig.1. The tetra-pole sensor includes the assembly of two self-perpendicular electromagnets with pole pieces. The magnetic flux in each electromagnet is created by its own magnetizing coils respectively 1.1, 1.2 and 2.1, 2.2 respectively. The coils are fed by common-mode voltage from the control generator, controlled by embedded PC. The controller controls the amplitudes values of the sinusoidal currents in four coils respectively. Two feed back systems, controlled by the currents from additional coils 1.1F, 1.2F and 2.1F, 2.2F respectively in each channel X or Y, provide for the stable magnetic flux values independently on magnetic properties of the material under test and lift off. Therefore in the probe's central part, where the flexible pick-up sensor 3 is installed, the applied magnetic field vector will swing according to amplitude values in all four coils. So the BN measurements are implemented under the given applied magnetic field or magnetic flux values. The display embedded into the instrument represents the angle dependence of BN intensity in one of two selected modes with the corresponding diagram.

Summarizing the introduced capabilities of the tetra-pole sensor, integrated in the Introscan, results in the following advantages:

- two operation modes provided specimen magnetization under stable applied magnetic field or magnetic flux values give the opportunity to dejam, due to random lift-off or magnetic texture of the test material;
- sensor affordability to surface shapes;
- on-line plotting of DD in the instrument display;
- angle scanning and on-line plotting of DD if the calibration function is known;

- adjusting and verification technology is as well developed;
- easy facilities to transmit DD into the usual PC.

The experiments have been implemented to investigate the behavior of the DD of BN in the specimen under uni-axial bending with compression and tension up to the tensile stress values. The specimen, made of low alloyed high strength steel 300M after quenching, tempering, grinding and polishing was subjected to the cantilever bending. Its yield stress is 2140 Mpa. The DD of BN were measured in two described modes. It was observed that DD shapes strongly depend upon applied magnetic field amplitudes values. Simple mental analysis shows the importance of a perfect choice for this parameter during bi-axial magnetization, much more tough than in uni-axial case. The special optimization procedure was developed to facilitate providing a better choice. The idea of this procedure is to measure and plot the diagram, which is the dependence of the BN intensity, ***E***, upon the current value, ***I***, in the excitation coil, and then the optimal current choice will be the value, which is about 0.7 of the maximum value of BN intensity. The instrument helps to implement this function automatically simultaneously with plotting the diagram in the instrument display.

Measurement, recording and plotting of DD with tetra-pole sensor and Introscan is easy and fast. In this paragraph some examples of DD of BN intensity are shown. Fig. 2 illustrates two typical examples of directional diagrams of BN intensity for the sheets from transformer steel in the random-oriented and textured conditions. The angle scan was provided within the angle range from 0 to 180^0. The deflection of the random-oriented diagram from the circle shows the presence of residual texture in the sheet. The changes in the diagrams are very large and the dip in the hard direction (vertical) is dramatically distinguished from the BN intensity values in the easy one. The texture direction is as well very clear. The Series of experiments have been provided with the high strength low alloy steel 300M in the condition after heat hardening and low temperature drawback. In this condition it has yield strength 2176 Mpa. The plate

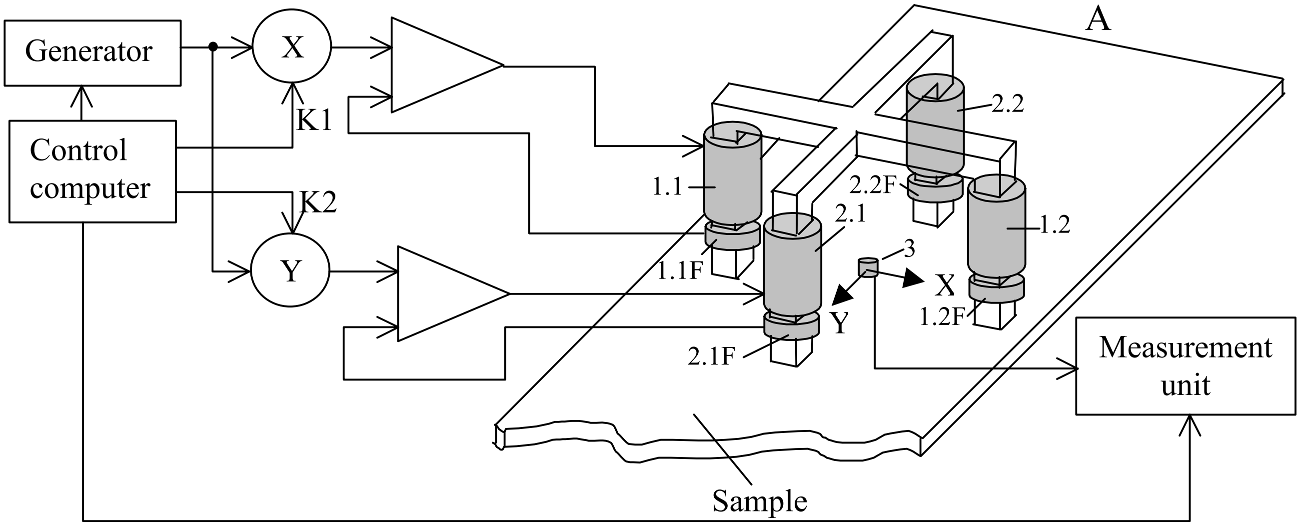

Fig. 1. The chart, which shows the tetra-pole probe, established on a plate, and the block diagram of the control system. 1.1; 1.2 - Electromagnet coils "X", 2.1; 2.2 - Electromagnet coils "Y", 1.1F; 1.2F - Feed back coils "X", 2.1F; 2.2F - Feed back coils "X", 3 - Pick up coil. A - location of the jammed end of the plate, subjected to bending

250x35x5,5 mm was then fine grinded and polished. Then it was subjected to cantilever bending by tension and compression up to the yield strength point like is shown in fig 1. Fig 3 presents some selected DD of BN intensity under different stress values applied to the specimen surface in the pick-up coil domain. The left block of diagrams illustrates the DD in the plate after step-wise tension, while the right block – after compression. Both blocks contain the diagrams with zero level stresses, obtained while the stress are grow up and drops respectively. The stress values are shown in the diagrams legends.

It is interesting to point out that the product spaces along direction close to 45^0 are clearly defined in the diagrams. They coincide with the easy shear direction in the uni-axial loading mode.

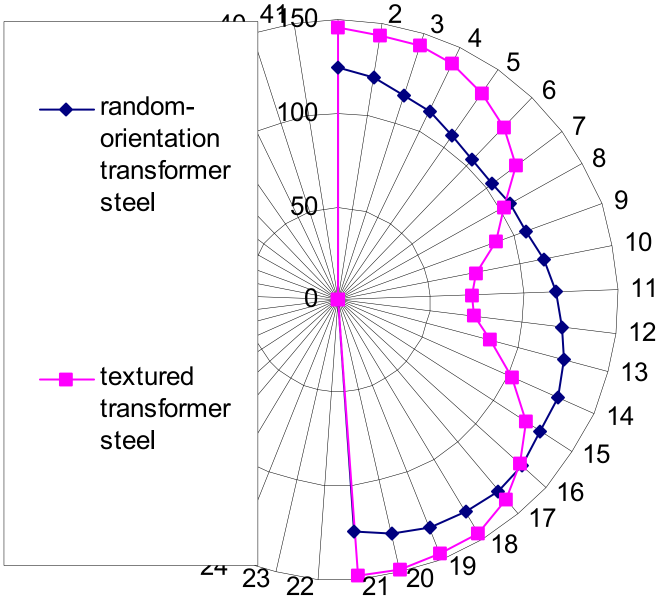

Fig.2. Directional diagram of BN intensity for random-oriented and textured transformer steel, recorded by Introscan with tetra-pole probe. The deflection of the random-oriented diagram from the circle shows the presence of residual texture in the sheet.

Discussion. Among a couple of implemented experiments we selected several shown above. To summarize the integrated experience, it is reasonable to represent some typical directional diagrams of BN intensity - a kind of a DD atlas, which characterize frequently occurring cases of texture and plane stress state conditions (Fig.4). Of course, this list in no case pretends for completeness, but from our point gives the rough idea for predicting a test material anisotropy condition, both qualitative and quantitative. In fact it can be observed, that sometimes small changes of external load result in substantial changes in DD contours and vise verse. This fact is a consequence of non linear function ***E(I),*** appearance of local or global plastic deformation and violating the plane stress condition in a test specimen. All these disturbances should be taken into consideration while evaluating experimental results.

Some new information can be also drawn from the analysis of product spaces domains for different diagrams. If there is no possibility to provide measurements with several loads, the DD, obtained with a standard specimen before test, can be taken for product spaces estimate. Neglecting the mentioned non linearity these product spaces domain characterize roughly easy shear direction in test area.

The inverse problem solution by combining together the experimental DD, ***E(I)*** function and Moor rule, which impose constraints on the behavior of plane stress tensor components, it is possible to reconstruct an angle distribution of the last in a test domain [8].

The family of DD can stay as a calibration data set V_σ^c. Any of it represents a part of BN signal which is caused by stress variation. Complete signal value includes also a part corresponding to the zero stress level $V_s^c(\rho_{ij})$, where ρ_{ij} - a microstructure factor which generally can also be a tensor value. Supposing both parts being additive a complete BN signal can be presented in the form:

$$V^c = V_\sigma^c\left(\sigma_{ij}\right) + V_s^c\left(\rho_{ij}\right)$$

(1)

Calculation of the actual planar stress tensor components can be implemented by the solution of the inverse problem in the form of (1) using specific a priori knowledge and the calculated signal values taken from the calibration data set using interpolated values in the inter space between experimental points. By integrating data and prior into an inverse problem solution one can get the variational equation for the solution of inverse problem with regard to planar stress tensor components

$$\hat{\sigma}_i = \arg\min \left\{ \sum_i \left[V_\sigma^c\left(\sigma_i\right) + V_s^c\left(\rho_i\right) - V_i^m \right]^2 \right\} + \gamma \left[\sum_i \left(\sigma_i^\alpha + \sigma_i^\beta\right) - \left(\sigma_1 + \sigma_2\right) \right] + \eta \left[\sum_i \left(\rho_{i+1} - 2\rho_i + \rho_{i-1}\right) \right]$$

(2)

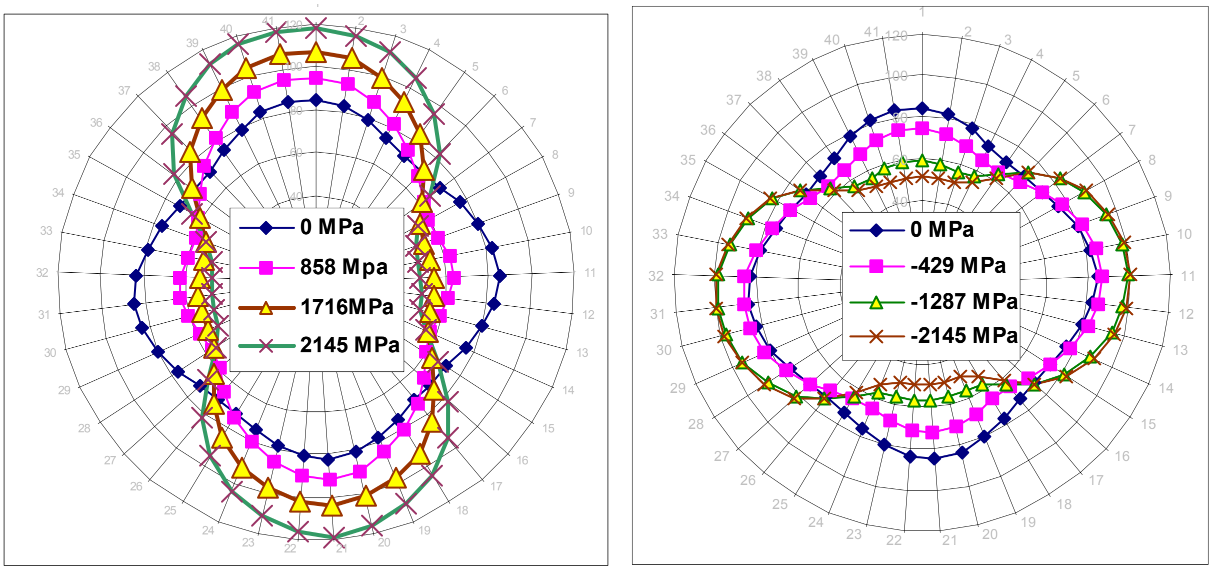

Fig.3. Directional diagrams of BN under different applied bending deformation of steel 300M plate: the functions of BN intensity upon a direction of excitation magnetic field vector. Vertical axis on the diagrams coincides with the longitudinal plate axis. Left diagram – tension, right – compression. The product spaces along direction close to 45^0 are clearly defined in the diagrams

where σ_i - angle sampled stress values; superscripts α and β characterize self perpendicular stress components; σ_1 and σ_2 denote principal stress values, γ and η correspond to the weighting factors adding some weight to both a priori functionals (second and third terms in equation (4)). Both last terms express in the formal way important features of the planar stress tensor components and microstructure characteristics: the 2nd one gives the iterative support to the stress angular functions satisfying to the basic law of the plane stress: $\sigma^{\alpha} + \sigma^{\beta} = \sigma_1 + \sigma_2$. The 3rd one expresses the smoothing condition for an angular dependence of microstructure material properties, what is necessary for the stability of the minimization procedure.

Solution of the inverse equation (4) gives the way to restore the function of angular distribution for planar stress tensor components compatible with main physical constraints.

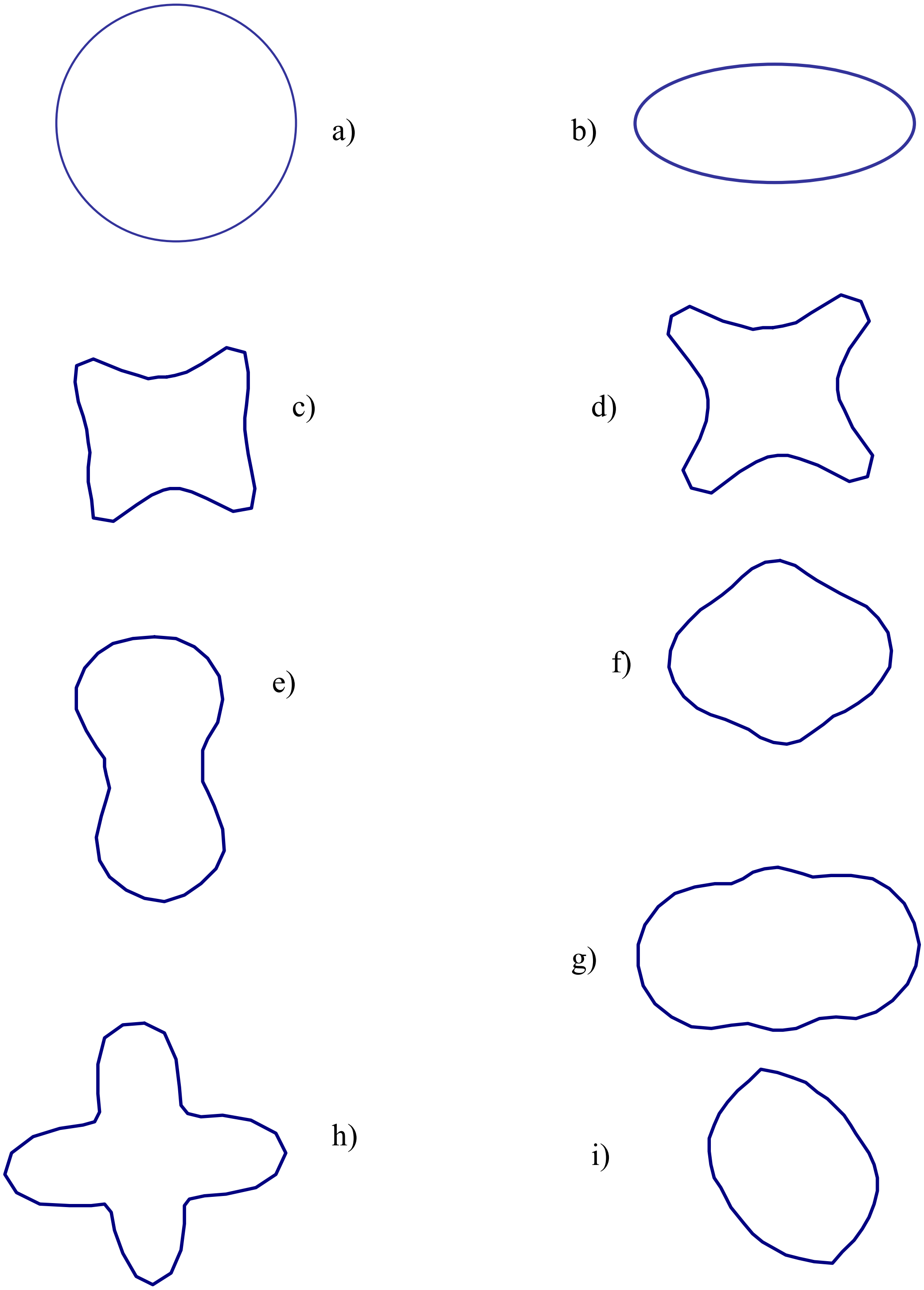

Fig.4. Typical examples of directional diagrams shapes for magnetic materials in various conditions: a) isotropic state; b) uni-axial tension or compression; c) bi-axial compression by two non equal orthogonal loads; d) bi-axial compression by two equal orthogonal loads; e) large uni-axial bending; f) bi-axial tension by two non equal orthogonal loads; g) small uni-axial bending; h) bi-axial tension by two equal orthogonal loads; i) weakly textured specimen with small applied tension.

Conclusion: New instrument Introscan, tetra-pole probe and the technique for fast and easy on-line measurement, plotting and recording of the functions of Barkhausen Noise intensity upon the angle of an excitation magnetic field vector direction, so called Directional Diagrams (DD) are developed. It is shown that DD shape is quantitatively and qualitatively characterizes the anisotropy behavior of a test material plane stresses and texture. This technique can be the experimental basis for the plane stress tensor components reconstruction using DD data and the calibration functions, made with the same acquisition system.

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