Tensor characteristics of intrinsic scattering magnetic field as an effective tool for strength diagnostics of steel products

V G Malinin1,4, N A Malinina1, V V Malinin2, A A Dimov1 and O A Malukhina3

1 Oryol State Agrarian University, 69, General Rodina St., Orel, 302019, Russia
2 Tupolev PJSC, 17, Academician Tupolev Embankment, Moscow, 105005, Russia
3 Yaroslav-the-Wise Novgorod State University, 41, ul. B. Sankt-Peterburgskaya, Veliky Novgorod, 173003, Russia

4 E-mail: malinin.mvg@yandex.ru

Abstract. On the basis of the methods of structural-analytical mesomechanics, tensor characteristics of the intrinsic magnetic field of scattering are formulated, their experimental substantiation is given, and studies allowing performing the operational quality control of steel products of responsible use are given.

1. Introduction
The method of magnetic memory of metals allows studying the structural and technological heredity of engineering products quickly and with good reliability. Based on this method, the authors developed a methodology for controlling the quality of new products [2, 3], with the aim of determining their predisposition to be damaged during operation.

This article presents a development of the magnetic memory method, introduces tensor parameters of the intrinsic scattering magnetic field (ISMF) based on which experimental studies of the zones of structural concentrators over the entire working part of steel bolts are performed. The data on the zones of structural concentrators in new bolted products are presented, which made it possible to develop an operational methodology for monitoring their quality.

2. Structural characteristics of the magneto-mechanical effect
In [1–5], the feasibility of using the magnetic memory method to solve the problem of determining the stress-strain state (SSS) of materials and products was convincingly substantiated, which allows us to analyze the development of zones of structural concentrators (ZSC) in the process of material loading based on the measurement of the intrinsic scattering magnetic field (ISMF) parameters. In view of the foregoing, an important task is the creation of experimental-theoretical models that reflect the basic laws of evolution of structural stresses based on recording parameters of the ISMF. It is necessary to introduce appropriate conceptual representations and mathematical tools.

Let us consider a possible solution to the problem. Functional relationships between parameters of different physical contents can exist only for mathematical objects of the same tensor valency according to the Curie Inhibition principle. We will consider the most common version of the problem for definiteness, when the structural and stress-strain state can be characterized by tensors of zero, first and second valency.
2.1. Scattering intrinsic magnetic field vector

By measuring the magnetic field strength $H_i$, at various points of the deformed body, it is possible to determine the distribution of $H_i$ over the coordinates of the test article. Experiments were performed on thin steel plates to verify the existence of ISMF in the sample, after deformation of the material as a vector object. We studied plates without concentrators and with various macroconcentrators in the form of central round and elliptical holes, side cuts of various configurations made of steel 3, steel 45, steel 09G2S. We used a commercially available specialized monitoring device ISMF developed by the enterprise OOO "Energodiagnostika" and a three-component flux-probe. In particular, a magnetometric stress concentration meter IKN-3M-12 was used, with a microprocessor-based recording device. $H_i$ measurements were performed at various points in the sample, and the components of the $H_i$ vector were scanned at each point, turning the sensor by 30°, 45°, 60°, and 90° degrees. Each experiment was repeated three times. The measurement results confirmed the invariance of $H_i$, i.e. the law of conservation of the tensor of the first rank was satisfied when the coordinate system was rotated

$$H'_i = a_{ik}H_k,$$

(1)

where $a_{ik}$ - are guide cosines. The measurement error according to the estimate of the invariant $(H_i H_i)$ 1/2 did not exceed (1-3)%, and the scatter for individual $H_i$ components did not exceed 5%. Moreover, the scatter was the smallest in those places where there was significant plastic deformation. The data obtained convince that the methods of measuring ISMF completely satisfy the tasks of studying the structural-mechanical state of the material.

2.2. Distortion tensor of the intrinsic scattering magnetic field

The next stage of experimental research was to measure the components of the ISMF over the entire working part of the deformable plate during loading. The dimensions of the working part of the plate were 60x120 2 mm. A square grid was applied with a cell size of 5 x 5 mm. The components of the vector $H_i$ were measured at the grid nodes; the total number was 11 x 11 = 121 knots. Three measurements of the $H_i$ components were performed in each node, and then the usual statistical processing was performed. The whole diagram of plate tension was obtained under conditions of step loading; the number of steps was 10-12, up to failure. The total number of measurements in each experiment was in the range of 1.5 –2 thousand. The obtained results on the distribution of the vector field $H_i$ made it possible to introduce into consideration the ISMF distortion tensor as a gradient from the intensity vector $H_i$ by the formula

$$H'_{ik} = \nabla_i H_k,$$

(2)

where $\nabla_i$ – Nabla operator [2].

Processing of the experimental data using the formula (2) made it possible to obtain an experimentally substantiated mathematical object characterizing the heterogeneity of the ISMF. The next step was to verify the parameters of $H_{ik}$ (2) experimentally to preserve $H_{ik}$ as a tensor of the second rank when the coordinate system is rotated by angles: 30°, 45°, 60°, and 90° degrees. The results of processing the obtained data showed satisfactory compliance with the conservation law

$$H'_{ik} = a_{ip}a_{kq}H_{pq},$$

(3)

The scatter in the values of the first, second, and third $H_{ik}$ invariants was within 15%, which confirmed the tensor character of the $H_{ik}$ parameters. It should be noted that these experimental studies required the creation of original snap-ins, each experiment lasted 4–5 hours. A special experimental study was carried out, confirming the tensor character of the introduced parameter $H_{ik}$, called the distortion of the intrinsic scattering magnetic field.

Based on the $H_{ik}$ distortion tensor, symmetric $H_{ik}^s$ and antisymmetric $H_{ik}^a$ tensors were introduced:

$$H_{ik}^s = \frac{1}{2}(\nabla_i H_k - \nabla_k H_i); H_{ik}^a = \frac{1}{2}(\nabla_i H_k - \nabla_k H_i).$$

(4)
Introduction $H^{ik}$ allows the development of symmetric structural mechanics in accordance with the traditional symmetric mechanics of a deformable solid. The introduction of the parameter $H^{ik}$ opens up the possibility of developing structural models that take into account moment structural stresses and the corresponding bending-torsion strains.

2.3. Tensor intensity of intrinsic scattering magnetic field

From the total distortion tensor $H_{ik}$ (3), we can distinguish the physical significant tensor $Z_{ik}$, called the tensor intensity of the ISMF in the form:

$$Z_{ik} = Z_{13} \delta_{i1} \delta_{k3} + Z_{23} \delta_{i2} \delta_{k3}.$$  \hspace{1cm} (5)

where $Z_{13} = H_{13}; Z_{23} = H_{23}; \delta_{ik}$ – is Kronecker symbol. Considering that the symmetric stress tensor is used in this work, it is advisable to construct a symmetric tensor

$$S_{ik} = \frac{1}{2} H_{13} (\delta_{i1} \delta_{k3} + \delta_{i3} \delta_{k1}) + \frac{1}{2} H_{23} (\delta_{i2} \delta_{k3} + \delta_{i3} \delta_{k2}).$$  \hspace{1cm} (6)

Cubic equation for determining the main values $S_{ik}(k = 1, 2, 3)$ is written as

$$S_{ki}^3 - J_1 S_{ki}^2 - J_2 S_{ki} - J_3 = 0;$$

where

$$J_1^{\frac{3}{2}} = S_{ii}; \quad J_2^{\frac{3}{2}} = S_{33}; \quad J_3^{\frac{3}{2}} = S_{11};$$

Solving the cubic equation, we obtain the following principal values of the tensor $S_{ik}$

$$S_{i,3}^{\frac{1}{2}} = \pm \frac{1}{2} \sqrt{S_{13}^2 + S_{23}^2}; \quad S_2 = 0; \quad S_1 \geq S_2 \geq S_3.$$  \hspace{1cm} (7)

Intensity $S_i$ of the tensor $S_{ik}$, and also the parameter $S_{\text{max}}^\tau$ is written as:

$$S_i = \sqrt{J_2^{\frac{3}{2}}} = \frac{1}{2} \sqrt{S_{13}^2 + S_{23}^2}; \quad S_{\text{max}}^\tau = \frac{1}{2} (S_1 - S_3) = \frac{1}{2} \sqrt{S_{13}^2 + S_{23}^2}.$$  \hspace{1cm} (7)

Analyzing relations (7), it can be noted that the symmetric part of the tensor intensity of ISMF (6) has only the second invariant different from zero $\frac{1}{2} S_{ik} S_{ik}$, through which the main values $S_1, S_3$ are expressed and also the parameters $S_{\text{max}}^\tau$ and $S_i$.

2.4. Structural criterion of the limiting state of a material in stress concentration zones (SCZ)

Let us give comments confirming the appropriateness of the introduced tensor intensity ISMF $Z_{ik}$ in the form (7) for the formulation of the criterion for destruction reflecting the influence of zones of structural concentrators [6]. The invariant $S_i = \frac{1}{2} (S_{ik} S_{ik})^{\frac{1}{2}}$ in the vicinity of the zone of the structural concentrator, with the accuracy up to a constant coefficient $\left( \frac{1}{\sqrt{2}} \right)$, coincides with the $K_{in}$ parameter called the gradient of the normal component of the intrinsic magnetic field $K_{in}$ [6–9]. The $K_{in}$ parameter in the magnetic memory method (MMM) plays a key role as a diagnostic parameter for assessing the state of a metal in stress concentration zones (SCZ) [6, 7]. Numerous experimental studies have made it possible to establish a relationship between the dislocation density $\rho$, strain $\varepsilon$, and the ISMF parameter $K_{in}$.

Figure 1 and figure 2 show the dependence of the dislocation density $\rho$ on the degree of plastic deformation $\varepsilon$, and figure 3 the dependence of the relative deformation $\varepsilon(1)$ and the gradient of the normal component of the $K_{in}$ scattering magnetic field (2) on the tensile stress $\sigma$ in the macroplastic region [6].
Figure 1. The dislocation structure of steel 10 after plastic deformation $\varepsilon$ under static loading: $a - \varepsilon = 2\%$, $\times 20000$; $b - \varepsilon = 6\%$, $\times 20000$ [6].

Figure 2. Dependence of the dislocation density $\rho$ along the line of stress concentration ($H_p = 0$) on the degree of plastic deformation $\varepsilon$ [6].

Figure 3. Dependences of the relative elongation $\varepsilon$ (1) and the gradient of the normal component of the $K_{in}$ scattering magnetic field (2) on tensile stresses $\sigma$ in the region of plastic deformation [6].

Comparing the experimental data presented in figure 2 and figure 3, it can be noted that the $K_{in}$ parameter, strain $\varepsilon$ and the corresponding dislocation density $\rho$, as a result of the action of actual stresses, are integral characteristics of the state of the metal of the product in SCZ [6]. It is known that the main sources of damage occurrence and development are SCZ, in which the processes of fatigue, corrosion and creep develop most intensively. As it is noted in [6], many years of experience in industrial research have revealed the existence of stable lines of sign reversal of the normal component of the ISMF stress $H_p$ (line $H_p = 0$) in local zones of metal damage. The geometrical place of the points where the parameter $H_p$ changes sign ($H_p = 0$) is called the line of stress concentration (LCN) in [6]. It is experimentally substantiated that LCN indicates the place of the most probable formation of microcracks and in the subsequent development of macrocracks.

A strength analysis of the quality of manufactured steel bolts for critical purposes is performed in the next section, based on the introduced tensor parameters.
Figure 4. Distribution of ISMF components (thick lines) and their gradients (thin lines) directed: a, b – along the axis of the bolt, c, d – along the normal to the surface, e, f – along the tangent to the diameter of the bolt, positions a, c, e – relate to a bolt with an increased density of defects, positions b, d, f – correspond to the permissible degree of heterogeneity of the structure.
3. The study of the quality of steel bolts

Two batches of new steel bolts from steel 40X GOST 4543 in the amount of 10 pieces were taken for the study, which passed the test control required by the adopted technology and were found suitable for use in critical structures. The necessary equipment was made for diagnostics using the magnetic memory method, a technique was developed and research was carried out. In each batch of 5 samples, one bolt was discovered having a pronounced defective structure more than an order of magnitude higher than the corresponding magnetic parameters characterizing the structural state of the remaining products.

A voltage concentration meter IKN-3M-12 was used for research, complete with a 12-channel fluxgate transducer and the "MMP-Sistema" software product. The following parameters were chosen as diagnostic parameters: the module of the vector of the measured intrinsic magnetic field (H), which made it possible to determine the coordinates of the point of the dangerous section of the bolt and the components of the magnetic distortion tensor, which characterize the gradients of the corresponding components of the ISMF vector, reflecting the most probable direction of crack occurrence. The measurement results are shown in the figures 4 a, b, c, d, e, f.

Analyzing the results presented in figure 4, it can be noted that in a dangerous section of a bolt with an increased defect density (figure 4, positions a, c, e) compared to a similar section of a bolt where there are no anomalies in the measured magnetic parameters (figure 4, positions b, d, f) differ qualitatively, both in the nature of the distribution of parameters of the ISMF, and in quantitative characteristics. Two practically mutually perpendicular directions with a pronounced localization of the module of the vector ISMF are clearly revealed. The greatest difference is revealed by the parameter Si. The modulus of vector intensity $S_i$ in a defective product is more than by 27 times than in a product of magnetless anomalies. The modulus of the intrinsic magnetic scattering field in these sections has a strong localization and differs by almost 10 times.

4. Conclusions

The tensor models of the ISMF are formulated and experimentally substantiated. The proposed tensor characteristics of the ISMF allow entering diagnostic parameters, which make it possible to perform rejection and select a poor-quality product in the express control mode for the distribution of the residual magnetization, which has developed naturally in the technological process of manufacturing bolts.

It is necessary to measure all components of the intrinsic scattering magnetic field strength and the components of the ISMF distortion tensor in order to further develop the method of non-destructive testing of critical steel objects, which will make it possible to use the invariant magnetic characteristics of the structural state as criteria.

References

[1] Dubov A A and Dubova A A 2006 Method of magnetic memory and control devices (Moscow: “Tisso” Publ) p 332

[2] Malinin V G, Malinina N A and Dimov A A 2015 Metodika eksperimental’nikh issledovanii strukturo-makhanicheskikh kharakteristik stal’nikh plastin s konzentratormi [Method of experimental research of structural and mechanical characteristics of steel plates with concentrators] Actualnie problemi stroitel’stva, stroitel’noi industrii i promischlennosti (Moscow) 65–66

[3] Dubov A A, Malinin V G, Malinin V V and Malinina N A 2009 Magnitomechanicheskii effect i ego tenzornoe kharakteristiki. Diagnostica oborudovaniya i konstrukcii c ispolzovaniem magnetnoi pamjati metalla [Magnetomechanical effect and its tensor characteristics. Diagnostics of equipment and structures using metal magnetic memory] Sbornik mater. 5th mezhdunarodnaja nauchno-tekhnicheskaja conf. (M: Energodiagnostika) pp 43–46

[4] Ivanov V E and Koveshnikov A V 2018 Longitudinal magneto-optical images of stray fields on the surfaces of hard magnetic elements Journal of Magnetism and Magnetic Materials 460 153–159

[5] Ivanov V E, Koveshnikov A V and Andreev S V 2017 Osobennosti magnitoopticheskikh
izobrazhenii polei rasseyaniya magnitov razlichnikh geometricheskikh form Fizika metallov I metallovedenie 8(118) 772–778

[6] Vlasov V T and Dubov A A 2007 Teorija prozessa “deformazija-razruschenie Fizicheskie kriterii predelnogo sostojanija metalla” (Moscow: “Tisso” Publ) p 517

[7] Vlasov V T and Dubov A A 2004 Fizicheskie osnovi metoda magnitnoi pamyati metallov (Moscow: “Tisso” Publ) p 424

[8] Novopaschin M D 1987 Gradientnii kriterii tekuchesti elementov konstrukzii s konzentratorami naprajagenii [Gradient criterions for local flow of metal structure elements with stress concentrators] Modelirovanie v mekhnike: sbornik nauchnikh trudov (Novosibirsk) vol 1 3 131–140

[9] Leonov M J 1981 Mekhanika deformazii i razruschenii (Frunze: Ilim) p 236