Magnetic non-destructive testing of residual stresses in low carbon steels

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Abstract. A new calibration-free magnetic method and a measuring system for residual stresses monitoring in low carbon steels have been developed. The method is based on the fact that during the action of compressive stresses in the material an “easy plane” magnetic texture appears. Magnetic texture affects the processes of magnetization reversal of the testing object in such a way that two or three maxima on the curves of differential $\mu_d(H)$ or reversible $\mu_{rev}(H)$ magnetic permeabilities appear. The fields of the maxima are associated with the magnetoelastic field and residual stresses. To increase the reliability of testing results and simplify the evaluation of residual stresses in testing objects, it was proposed to use the method of subtracting experimental $\mu_d(H)$ curves measured in the zones of action of compressive stresses and in the object under test without stresses. The method can also be used to estimate residual tensile stresses that are the most dangerous for steel structures.

1. Introduction
Residual stresses can cause the growth of fatigue cracks and the construction destruction [1]. Especially, it is important to determine the level of stresses in objects whose documentation life is close to an end. Such testing method helps to extend the service life. Among all non-destructive testing (NDT) methods for monitoring the residual stresses of steel constructions the magnetic methods are the most frequently used [2-5]. The magnetoelastic and magnetostrictive effects are the base for the magnetic methods for the determination of stresses. Despite the fact that magnetic methods based on the determination of hysteresis-loop parameters and Barkhausen noise are highly sensitive to stresses, there are two unresolved problems: 1) it is necessary to do a calibration procedure for all magnetic methods; 2) effects of structural factors on the magnetic parameters and the impossibility of experimental evaluation of the critical magnetic field of the 90-degree domain walls (DW) motion.

There was developed a new unique magnetic technique and instrument [6-8] for determination of residual stresses in low carbon steels. The uniqueness of the method is that it does not require a pre-calibration procedure, i.e. it’s a calibration-free method. The technique is developed from the phenomenon that under compressive stresses the “easy plane” magnetic texture perpendicular to the action of stresses appears in the material. The magnetic texture affects on the magnetization reversal processes. In this case, two or three maxima are observed in the field dependences of the differential magnetic permeability $\mu_d(H)$ and of the reversible magnetic permeability $\mu_{rev}(H)$. The fields of extrema on the $\mu_d(H)$ and $\mu_{rev}(H)$ curves are associated with critical fields of 90- and 180-degree DWs motion. Since mechanical stresses only affect the displacement of 90-degree DWs, it was necessary to separate the contribution of two types of DWs to the processes of magnetization reversal and determine the critical fields of 90-degree DWs motion. The results of such work were published in [9]. The experimental curves $\mu_d(H)$ were processed by two methods: approximation by the three pseudo-Voight...
peaks and method of subtraction of curves measured in the unloaded and elastic-loaded states [9]. The use of the curves subtraction method in practice turned out to be convenient. The essence of the method was in the fact that at the first stage, the $\mu_d(H, \sigma_0=0)$ curve was measured without applied stresses. At the second stage, an elastic tensile stress of such magnitude was applied to the sample in order to compensate for all residual compressive stresses, i.e. $\sigma_0=|\sigma_{\text{im}}|$. The $\mu_d(H, \sigma_0=\sigma_{\text{im}})$ curve was measured. In this case, only the 180-degree DWs motion contributed to the field dependence of magnetic permeability [10]. Next, the curve $\mu_d(H, \sigma_0=\sigma_{\text{im}})$ was subtracted from the initial curve $\mu_d(H, \sigma_0=0)$:

$$\Delta \mu_d(H, \sigma_0) = \mu_d(H, \sigma_0=0) - \mu_d(H, \sigma_0=\sigma_{\text{im}}).$$

(1)

The $\sigma_{\text{im}}$ values for each of the plastically deformed samples were determined from the minimum of the dependence of the coercive force on the stresses $H_c(\sigma_0)$ [11]. The resulting curve $\Delta \mu_d(H, \sigma_0)$ had three extrema, the left and right of which were associated with displacements of only 90-degree DWs. Having determined the fields of these extrema $H_1^*$ and $H_2^*$, we calculated the values of the magnetoelastic field $H_\sigma$ and the residual stresses $\sigma_i$:

$$H_\sigma = - (H_1^* + |H_2^*|) / 1.64,$$

(2)

$$\sigma_i = \frac{2}{3} H_\sigma M_s / \lambda_{100},$$

(3)

where $M_s$ is the saturation magnetization, $\lambda_{100}$ is the magnetostriction constant.

However, in practice, the testing object is often impossible to subject to elastic stretching to obtain an experimental curve $\mu_d(H, \sigma_0=\sigma_{\text{im}})$. For the method of subtraction of curves described above, it’s necessary to use another curve. This work is dedicated to solving this problem.

2. Experimental results and discussion

The experimental results were obtained on samples of St3 low-carbon steel (having compositions of 0.14-0.22% C, 0.05-0.17% Si, 0.4-0.65% Mn, <0.3% Ni, Cu, Cr, <0.08% As, <0.05% S, <0.04% P). The sizes of the samples in the initial state were: length 267 mm, cross-sectional area $2 \times 3 \text{ mm}^2$. After annealing in vacuum at 650 °C for two hours and slow cooling in a furnace, the samples were plastically stretched and had different degrees of elongation from 0.5 to 8.4%. Additionally, the undeformed sample was examined. The dependences of the differential magnetic permeability on the magnetic field $\mu_d(H)$ were measured using the experimental setup, the scheme of which is shown in figure 1. The magnetization reversal of the samples was carried out in a solenoid at a field change frequency of $5 \times 10^{-3}$ Hz. The maximum magnetic field in the solenoid was ±135 A/cm, which was enough to magnetize the samples to technical saturation. The field dependences $\mu_d(H)$ were measured by a differential coil located in the centre of the sample. The coil signal was amplified, and after that it was processed by ADC and PC (figure 1). The PowerGraph 3.3 software was used for visualization and primary data processing. The ends of the samples were fixed in the grippers of the machine for mechanical testing. Tensile elastic stresses were applied to the samples.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** The experimental setup: 1 – the sample, 2 – measurement coil, 3 – solenoid, A – amplifier, G – generator, PA – power amplifier, ADC – analog to digital converter, PC – computer.
In figure 2 for the sample with an elongation of 7.4% are given: a) the initial curve $\mu_d(H, \sigma_0=0)$ with two peaks (figure 2a, curve 1); b) the curve $\mu_d(H, \sigma_0=\sigma_i^m)$ with one maximum in small negative field (figure 2a, curve 2); c) the result of the subtraction according to equation (1) (figure 2b). The resulting curve $\Delta \mu_d(H, \sigma_0)$ in figure 2b has three extrema, two of which in the fields $H_1^*$ and $H_2^*$ are associated with only the 90-degree DWs motion. The values of the fields $H_1^*$ and $H_2^*$ were 16 A/cm and -17.4 A/cm, respectively. From equations (2) and (3), the values of the magnetoelastic field $H_\sigma = -20.4$ A/cm and residual stresses $\sigma_i = -147$ MPa were obtained.

In order to apply the algorithm described above to real steel structures, it is necessary to find a replacement for curve 2 in figure 2a, obtained on a plastically deformed sample under the action of an elastic stretching stress. We compared the $\mu_d(H)$ curve for the non-deformed specimen from St3 steel with the $\mu_d(H)$ curves for the deformed specimens subjected to elastic tension. Figure 3 shows the field dependences of the differential magnetic permeability obtained on an annealed undeformed sample at $\sigma_0=0$ (curve 1) and on a deformed sample with an elongation of 7.4% under the action of elastic tension $\sigma_0 = \sigma_i^m$ (curve 2). The curve 1 (figure 3) had a maximum in the field of -1.9 A/cm, the curve 2 - in the field of -2.4 A/cm. So the difference in the fields of the maxima of curves 1 and 2 (figure 3) was 0.5 A/cm, which was less than the measurement error of the field, which was 1 A/cm. Since the fields of maxima $H_1^*$ and $H_2^*$ (figure 2b) associated with irreversible displacements of 90-degree DWs were much larger than the fields of maxima of curves 1 and 2 (figure 3), it is reasonable to assume that the subtraction of both curves from the initial curve $\mu_d(H, \sigma_0=0)$ should lead to a similar result.

**Figure 2.** The dependences of the differential permeability $\mu_d$ on the reversal field $H$: (a) the curve 1 is the initial dependence $\mu_d(H, \sigma_0=0)$ for a sample with elongation 7.4%; the curve 2 is the dependence of $\mu_d(H, \sigma_0=\sigma_i^m)$ under the action of an elastic tensile stresses $\sigma_i^m = 300$ MPa; (b) the curve $\Delta \mu_d(H, \sigma_0)$.

**Figure 3.** The $\mu_d(H)$ curves for different values of elongation of St3 low-carbon steel: the curve (1) was obtained on an annealed undeformed sample with $\sigma_0=0$; the curve (2) was obtained on a plastically deformed sample with an elongation of 7.4% under the elastic tension $\sigma_0 = \sigma_i^m$. 

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The result of the curves 1 and 2 subtraction from the initial curve $\mu_d(H, \sigma_0=0)$ is shown in figure 4.

**Figure 4.** The result of subtracting of curves 1 and 2 from the initial curve (figure 3), for a specimen of low-carbon St3 steel with an elongation of 7.4%.

As can be seen from figure 4, the fields of the right extremes coincide, and the fields of the left extremes differ by 2.7 A/cm. The mean field obtained for curves 1 and 2 differ from each other by 8%. Such difference will be between the residual stresses, if for their calculations, instead of the curve 2 (figure 3), we use for the curve 1 (figure 3) measured for example on the undeformed area of the testing object. The error in determination of residual stresses up to 10% is quite acceptable for an indirect magnetic NDT that does not require preliminary calibration on standard samples. Therefore, for the developed method of determination of residual stresses and calculation of the result according to expression (1), it can be used any curves shown in figure 3.

Also for the subtraction method it is possible to use curves $\mu_d(H)$ measured along and across the direction of deformation of the tested object. In the unloaded state, along the direction of deformation there will be compressive residual stresses $\sigma^-$, and across the direction of deformation - tensile residual stresses $\sigma^+$ [12]:

$$\sigma^+ = -\nu \sigma^- \approx -0.3 \sigma^-,$$

where $\nu$ is the Poisson coefficient [12]. So the method proposed for determination of residual compressive stresses in steels is fully applicable to the case when the residual stresses are tensile. In this case, across the measurement direction of residual tensile stresses $\sigma^+$ action, residual compressive stresses $\sigma^-$ will act and two peaks will be observed on the curves $\mu_d(H)$. After the procedure of subtracting curves according to equation (1) and using relations (2) and (3), the stress values $\sigma^-$ can be found. The magnitude of the tensile residual stresses in the direction perpendicular to the direction of the action of the residual compressive stresses will be equal to $\sigma^+ = -0.3 \sigma^-$. In the case when two peaks are not observed in the dependence $\mu_d(H)$ in any measurement directions, there are no any residual stresses or only tensile stresses in a local place of the tested object.

3. **Mobile measuring system**

For the practical implementation of the residual stress determination method, a mobile version of a measuring system (figure 5) was developed. Structurally, the system consists of two parts: the primary transducer and the electronic unit. One of the main part of the attached primary transducer is a U-shaped electromagnet. The magnetic core is made of soft magnetic material. The dimensions of the poles are 12x28 mm, the interpolar distance is 29 mm. To measure the internal magnetic field in a
tested object, a Hall sensor IM 102 A1-1 is used (manufactured by VEGA-FLEX LLC, St. Petersburg, Russia), installed between the poles of a U-shaped electromagnet.

Figure 5. Mobile measurement system.

Valid measurement of the internal magnetic field is possible if the cross-sectional area of the poles is larger or comparable to the cross-sectional area of the tested object. To test massive objects, it is necessary to select the appropriate electromagnet size. The Hall sensor has a spring-loaded suspension to ensure mechanical contact with the surface of the test object. A measuring coil with the turns number of 500 is wound on the magnetic core. The signals from the measuring coil and the Hall sensor are amplified and passed to the ADC board. Measurement results of $\mu_d(H)$ curves are displayed on a laptop screen (figure 6).

Figure 6. The main user interface window of the measuring system software.

The electronic unit is placed in a portable suitcase. The electronic unit consists of a power amplifier, two pre-amplifiers, an NI USB-6211 ADC/DAC control board and a laptop. All components of the system (with the exception of a laptop and an ADC / DAC board) are powered by two sealed lead-acid batteries with a capacity of 7 A·h. The time of continuous operation of the complex is at least 8 hours. The mass of the system does not exceed 7 kg.

The primary transducer of the measurement system is locating on the tested object and remagnetizing it along the major hysteresis loop. The surface of the tested object should be pre-cleaned from non-ferromagnetic coatings and contaminants. Poles of electromagnet should fit snugly
to the surface of the tested object. To ensure contact with the radial surfaces, the corresponding replaceable tips are selected. The time of measurement is about 1 minute. The software of the measurement system was developed in the NI LabVIEW 13.0 environment.

4. Summary
As a result of research, a new calibration-free magnetic method and measurement system for monitoring residual mechanical stresses in low-carbon steels have been developed. Testing procedure in this method consists of the following steps:

- The presence of residual compressive stresses in the local place of the object under testing is determined by the shape of the $\mu_d(H)$ curves.
- If there are two maxima on the curve, this means the presence of residual mechanical stresses in the direction determined by the direction of the magnetization reversal.
- The largest fields of the maxima correspond to the greatest residual compressive stresses. In the perpendicular direction, as a rule, tensile residual stresses will act and a single extreme will be observed on the $\mu_d(H)$ curve, due to a predominantly irreversible displacement of 180-degree DWs.
- To estimate the magnitude of residual compressive stresses, it is necessary to measure the initial curve $\mu_d(H,\sigma_i=0)$, as well as the curve $\mu_d(H)$ either in the perpendicular direction, or the curve on the section of the object being monitored without mechanical stresses. Next, carry out the subtraction of the curves according to equation (1) and get the resulting curve $\Delta\mu_d(H,\sigma_i)$.
- From the resulting curve, the extrema fields $H_1^+$ and $H_2^+$ are determined and the values of the magnetoelastic field $H_0$ and the residual stresses $\sigma_i$ are calculated according to equations (2) and (3), respectively.
- In some cases the developed magnetic method allows estimating a tensile residual stresses $\sigma^+\approx 0.3 \sigma^-$ in a local place of the tested object.

Acknowledgments
This work was carried out within the state assignment of Minobrnauki of Russia (the theme 'Diagnostics' No. AAAA-A18-118020690196-3).

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