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Estimation of residual compressive stresses in deformed U8 steels with coarse-plate perlite by field dependences of magnetic permeability

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The physical reasons for the formation of peaks of that part of the magnetic permeability, which is caused by transitions of only 90-degree domain boundaries $\mu_{90}(H_0)$ in deformed steel U8 with coarse-plate perlite when the field changes along the back of the hysteresis loop, are considered. It is shown that the orientation relations of the Patch-Pitch between single-crystal ferrite and cementite plates in U8 steel lead to the appearance of a constant angle between the magnetic moments of these plates and, consequently, to the appearance of corresponding local scattering fields. The latter can significantly affect the values of the peak fields of the curve $\mu_{90}(H_0)$. Theoretical expressions for these fields containing contributions of scattering fields that should be taken into account when determining residual compressive stresses are obtained. It is also shown that to determine the residual stresses, two expressions for peak fields are not enough, and additional experiments are needed, as which it is proposed to use the dependences of the coercive force on elastic tensile stresses. This leads to a complication of the algorithm for determining residual compressive stresses in comparison with the case of low-carbon steels. A method for estimating the values of local scattering fields in the ferrite parts of U8 steel grains with residual compressive stresses is proposed.

Keywords: residual compressive stresses, deformed steel U8 with coarse-plate perlite, magnetic field, magnetization, magnetic permeability, 90-degree domain boundaries (DB), large-angle vicinity(LAV) and small-angle (SAV) grain boundaries of steel, orientation relations of the Patch-Pitch.

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Introduction

Eutectoid steel U8 is widely used in industry (see, for example, [1,2]), so the control of residual compressive stresses σ_i in structures made of this steel is important. Depending on the heat treatment, it may have lamellar and globular perlite structures with different properties. For example, steel with the structure of lamellar perlite, unlike steel with globular perlite, has increased strength, but low ductility with high brittleness. Its properties largely depend on the distance between the ferrite and cementite plates [3,4]. A significant number of studies are devoted to plastic deformation of pearlite steels [5], as a result of which large residual compressive stresses arise in it, which can affect the residual life of U8 steel products.

In [6], the sensitivity of magnetic properties to the structure of U8 steel was studied, but this is not it was used to determine residual stresses.

The authors of [7–9] tried to link changes in the magnetic properties of U8 steel with the degree of plastic deformation and the percentage of carbon: they investigated changes in hysteresis loops, field dependences of differential and reversible magnetic permeability, residual magnetization, and magnetostriction. The studies contain valuable results, but nevertheless do not address the issue of evaluation of residual mechanical stresses.

This paper considers a magnetic method of non-destructive testing (NDT) of these stresses based on the use of the dependence of the reversible magnetic permeability on the field H_0 when the latter changes along the back of the hysteresis loop. It is taken into account that each grain in steel U8 with coarse-plate perlite is an alternation of single-crystal plates of ferrite F and cementite C with certain orientation relationships (OR) between their axes [1,2]. Next, we will focus on the Petch-Pitch OR (PP OR), as the most probable in the case of coarse-plate perlite [10], and in terms of the magnetic permeability $\mu(H)$ on its part associated with the irreversible transitions of only 90-degree domain boundaries (DB) when the magnetic fields changes along the back of the hysteresis loop: $\mu_{90}(H_0)$. The method of such separation of $\mu_{90}(H_0)$ from the general curve $\mu(H_0)$ was developed in [11,12].

The magnetic moments of ferrite (M_f) and cementite (M_c) in the region of the curve peak fields $\mu_{90}(H_0)$ are oriented each in their own light directions: M_F in the direction $[100]_f$, where Young's modulus E_{100}, according to [13] is minimal. The Young's modulus is minimal $(E_{011})_c$ at C, and by analogy with F, it can be assumed that this direction to C is also the light axis of its magnetic moment. In this case, the angle between the vectors $\mathbf{M}_C$ and $\mathbf{M}_F$ is 23.7° according to [14]. We will further denote this angle α since we do not have an exact experimental confirmation obtained from magnetic measurements of the fact that the light direction of the magnetic moment M_c is oriented along the axis [011]. Note that this angle has a twofold role: in principle, a situation is possible when the direction of the light axis in perlite may change during deformation. Then this will lead to a change in the scattering fields and, consequently, to a change in the fields of the peaks of magnetic permeability. In this case, the phenomena studied here will also be of interest to metal scientists.

As a result, the PP OR determines the initial angle between the moments M_f and M_c, as well as the components of these vectors perpendicular to the planes of the plates F and C: $\mathbf{M}_f^{\perp}$ and $\mathbf{M}_c^{\perp}$ defining the corresponding scattering fields.

Since C is a magnetically rigid ferromagnet [6], then in the area of the peak fields of the curve $\mu_{90}(H_0)$, the vector $\mathbf{M}_c$, unlike M_f, should not change its direction. At the same time, any irreversible 90-degree transition of the vector $\mathbf{M}_f$ in ferrite plates should be accompanied by a change in the angle between the moments M_f and M_c by 90° and, consequently, the local field scattering in a given grain of steel.

As a result, contributions from local scattering fields H_{MST} caused by magnetic charges at the interface of plates F and C are added to the values of peak fields determined by residual stresses (as was the case in low-carbon steels [11,12]). Determination of the contributions of residual stresses and scattering fields from the experimentally obtained values of the peak fields of the curve $\mu_{90}(H_0)$ in deformed U8 steels with coarse-plate perlite is the main task of this work.

1. Conditions for the appearance of residual compressive stresses

Residual compressive stresses of the first kind $\sigma_i < 0$ are formed in each pair of grains „1" and „2" with a large-angle boundary (LAB — large-angle boundaries) [15] and in the one in which Young's modulus is larger: i.e., for $E_2 > E_1$ in grain 2 (it is referred naturally to the ferrite parts of these grains with E_2 with an angle between the field and $\mathbf{M}_f$ equal to θ_2) The reason for this is the fact that the same elastic deformation [11,12,15] always occurs in any pair of grains with LAB when elastic stresses are applied or removed. This results in

$$\sigma_i(\varepsilon_{\mathrm{pl}}) = -\varepsilon_u'[E(\theta_2) - E(\theta_1)],$$

$$\varepsilon_u = \sigma_{\mathrm{Y}}(\varepsilon_{\mathrm{pl}})/E^*; \quad \varepsilon_u' = \sigma_i^m/E^*. \tag{1}$$

Here ε_u — complete deformation of unloading after plastic stretching, ε_u' — that part of it that is associated with the maximum values of residual compressive stresses of the first kind, E^* — the average Young modulus of a polycrystal steel U8, $\theta_2 > \theta_1$ — angles of light axes M_f in plates F with a magnetic field in any pair of grains with LAB, $\varepsilon_{\mathrm{pl}}$ — plastic deformation. To simplify the subsequent calculations, following [11], we use a linear approximation of the dependence $E(\theta)$ of the form

$$E(\theta) = E_{100} + \gamma\theta, \tag{2}$$

where γ — the coefficient determined taking into account the value of E_{111} in iron. Formula (2) is valid with an accuracy of 4%, which is quite acceptable for our purposes. The expression (1) is noticeably simplified Taking into account (2) [11]:

$$\sigma_i(\varepsilon_{\mathrm{pl}}) = -\varepsilon_u'\gamma(\theta_2 - \theta_1) = -\varepsilon_u'\gamma\Delta\theta. \tag{3}$$

The value of $\Delta\theta$ generally varies from 0° to 55° (in iron BCC lattice). This interval includes all steel grains: both with LAB and LoAB (low-angle boundaries), i.e. with large-angle and small-angle boundaries [15]. Ensembles of these grains with LAB and LoAB in a steel polycrystal are separated by the value of $\Delta\theta = \Delta\theta_{\mathrm{LAB}} = 18.3°$ as follows from the analysis of the diagrams of paired neighborhoods [11]; as a result, the total interval of change in the magnitude of $\Delta\theta$ and angles θ_1 and θ_2 in grains with LAB is equal to

$$18.3° \le \Delta\theta \le 55°, \ 18.3° \le \theta_2 \le 55°, \ 0° \le \theta_1 \le 36.6°. \tag{4}$$

According to (3), (4) the residual stresses are maximal $\sigma_i^{\max}$ with $\Delta\theta = 55°$, they also decrease with a decrease of $\Delta\theta$, and they are equal to one third of this value with $\Delta\theta = \Delta\theta_{\mathrm{LAB}}$ [11,12]. On the other hand, with a decrease of $\Delta\theta$ from 55° the number of pairs of grains with LAB grows quadratically with$\Delta\theta$ and with $\Delta\theta = \Delta\theta_{\mathrm{LAB}}$ it reaches its maximum value [11], i.e.

$$\sigma_i(\Delta\theta_{\mathrm{LAB}}) = \sigma_i^m/3, \ N_{\mathrm{LAB}} = A(55° - \Delta\theta_{\mathrm{LAB}})^2. \tag{5}$$

Here A is the proportionality coefficient, and $N_{P\mathrm{LAB}}$ is the number of pairs of grains with LAB, which reaches a maximum at $\Delta\theta = \Delta\theta_{\mathrm{LAB}}$. This circumstance explains the presence of two peaks of the curve $\mu_{90}(H_0)$ at $H_0 = H_1 > 0$ and $H_0 = H_2 < 0$, by which the corresponding values $\sigma_i(\Delta\theta_{\mathrm{LAB}})$ [11] were determined in the deformed steel St3.

This mechanism of development of residual compressive stresses in steel after its plastic stretching, as well as the location of the maxima of the curve $\mu_{90}(H_0)$ (by H) is fully valid for steel U8 with coarse-plate perlite. The main difference from low-carbon steel St3 is the presence of single-crystal layers F and C in all grains of steel U8, having different magnetic and mechanical properties and a strictly defined angle between their magnetic moments $\mathbf{M}_f$ and $\mathbf{M}_c$, each of which is oriented along their light axes.

2. Results and discussion

Below we will be interested only in the fields of the peaks of the curve $\mu_{90}(H_0)$ ($H_1 > 0$ and $H_2 < 0$), taking place for grains with LAB and at $\Delta\theta = \Delta\theta_{\mathrm{LAB}}$. Taking this into

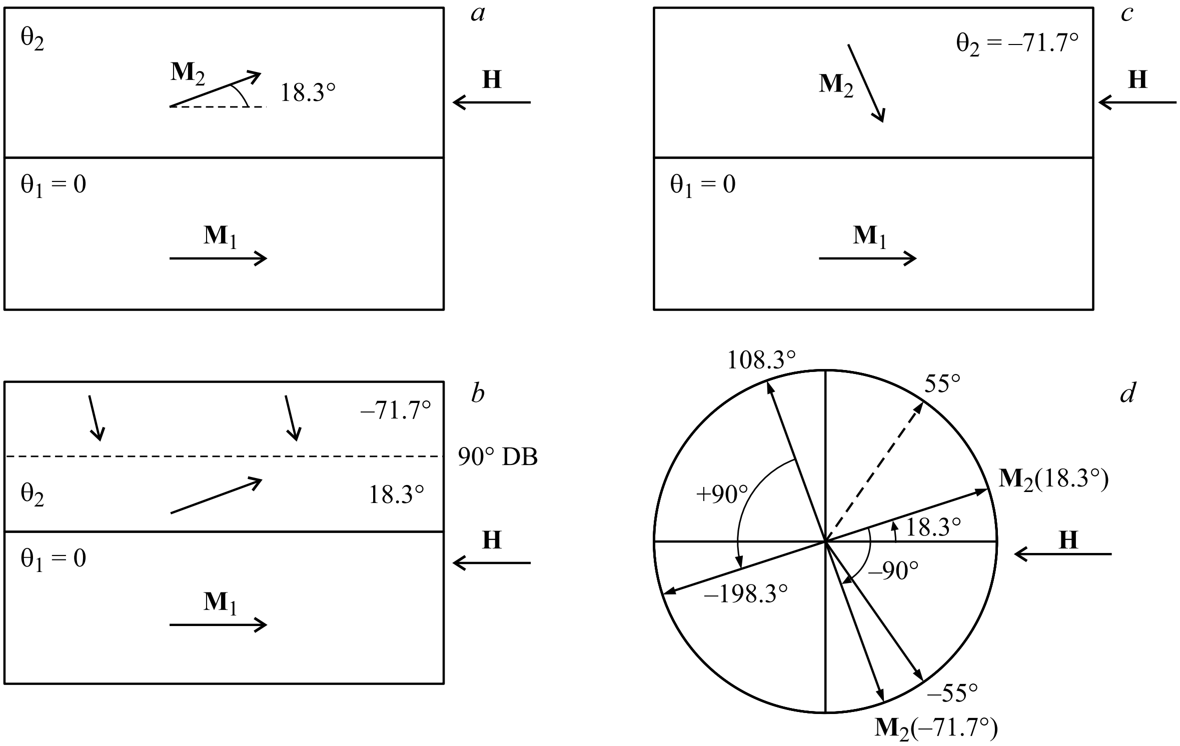

Figure 1. The following is schematically shown: *a* — the initial strawless state of a pair of grains with $\theta_2 = 18.3^\circ$ and $\theta_1 = 0^\circ$; *b* — grain with θ_2 in the presence of a 90-degree DB; *c* — the final domeless state with $\theta_2 = -71.7^\circ$ and $\theta_1 = 0^\circ$; *d* — the cross section of a spherical cone $\pm 55^\circ$ with a scheme of 90-degree transitions from the angle $\theta_2 = 18.3^\circ$.

account, we will write out the initial angles between the vectors $\mathbf{M}_f$, $\mathbf{M}_c$, $\mathbf{H}$, following from the PP OR:

$$\angle \mathbf{M}_f, \mathbf{M}_c = \alpha, \ \angle \mathbf{M}_f, \mathbf{H}_0 = 18.3^\circ,$$

$$\angle \mathbf{H}_0, (001)_c = 108.3^\circ - \alpha. \tag{6}$$

Considering the above, in (6) the value of the angle between the vectors $\mathbf{M}_f$ and $\mathbf{M}_c$ is not specified; in the final expressions for the peak fields, any of its specific values can be substituted instead of the angle α, including the value $\alpha = 23.7^\circ$; $(001)_c$ — plane of plates (C). It needs to be noted that the orientation of the external field $\mathbf{H}_0$, recorded by the experiment, remains constant at all 90-degree transitions M_f.

From the entire range of angle variation θ_2 (5) the calculations are performed only for $\theta_2 = 18.3^\circ$ which the only value corresponding to the peak of the curve $\mu_{90}(H_0)$. At its other values of (5), the change in magnetization in case of the 90-degree transitions is significantly less than at $\theta_2 = 18.3^\circ$, and contributes only to the broadening of the curve $\mu_{90}(H_0)$.

The general scheme of the 90-degree transition of the magnetic moment M_f at $\mathbf{H} > 0$ is shown in Fig. 1.

Figure 2 shows the changes in the magnitude of the component M_f perpendicular to the plate interface plane: $M_f^\perp$ creating magnetic charges $qM_f^\perp$, where $q = \pm 1$. The latter are considered positive if the vector $\mathbf{M}_f^\perp$ is directed to the plane of the interface of plates F and C and negative in the opposite case [16].

As noted above, the vector $\mathbf{M}_c$ does not change its direction in case of 90% transitions M_f. Since the equations for 90-degree transitions in F represent the equality of the energy difference of the initial and final states of the potential barrier energy (PB) for 90-degree DB [11,12], the magnetic charges $q\mathbf{M}_c^\perp$ with this subtraction of energies are mutually destroyed and, consequently, further are not taken into account.

Let us write expressions for the components M_f in the cases of the initial (Fig. 1, *a*, $\theta_2 = 18.3^\circ$) and final (Fig. 1, b, $\theta_2 = -71.7^\circ$) states for the field first peak H_1:

$$M_f^\perp(\theta_2 = -71.7^\circ) = M_f \sin\alpha, \ M_f^{\parallel} = -M_f \cos\alpha,$$

$$qM_f^\perp(\theta_2 = 18.3^\circ) = +M_f \cos\alpha, \ M_f^{\parallel} = M_f \sin\alpha. \tag{7}$$

The effective magnetic field across plates F and C will change compared to $H_0^\perp$ [16] by law

$$H_i^\perp = H_0^\perp - N_\perp^* q M_f^\perp. \tag{8}$$

Here $N_\perp^*$ is the effective demagnetization coefficient, which is much lower in a polycrystal of steel Y8 than in an isolated grain with θ_2 (where $N_\perp \sim 1$ [16]) due to the impact of scattering fields steel grains surrounding this pair of grains with LAB. Its value can be determined if the scattering field H_{MST} is found. The value $q = \pm 1$ determines the sign of

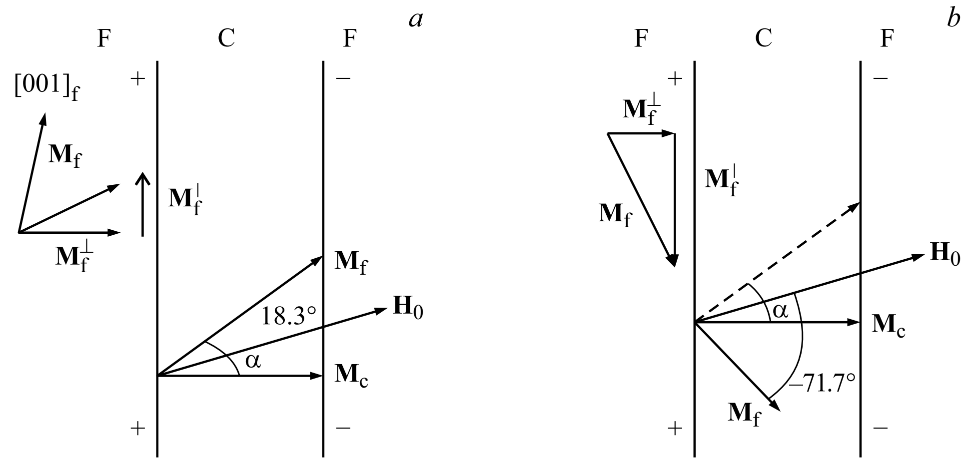

Figure 2. The scheme of distribution of magnetic charges on plates F and C before (a) and after (b) of 90-degree transition in steel U8 in grain with $\theta_2 = 18.3^\circ$ and $H_0 > 0$.

the magnetic charge and, accordingly, the direction of the scattering field.

Ratio (8) for the vector H is equivalent to the transition to the coordinate system associated with the planes of separation of plates F and C. In this system, the magnetic field energy EH is equal to

$$E_H = -H_0\|\mathrm{M}_f^{\|} - H_i^{\perp}\mathrm{M}_f^{\perp}. \qquad (9)$$

The values $\mathrm{M}_f^{\|}$ and $\mathrm{M}_f^{\perp}$ before and after the 90-degree transition are given above in (7), while the components of the field $\mathbf{H}_0$ do not change and in accordance with (6) are equal to

$$H_0^{\|} = H_0\cos(108.3^\circ - \alpha), \ H_0^{\perp} = H_0\sin(108.3^\circ - \alpha). \qquad (10)$$

The initial E_{INI} and final E_{FIN} energies at the first 90% transition from $\theta_2 = 18.3^\circ$ to the state $\theta_2 = -71.7^\circ$ are equal taking into account the ratios (7)−(10)

$$E_{\mathrm{INI}}/\mathrm{M}_f = -0.949H_0 + 0.568|H_\sigma| + H_{\mathrm{MST}}\cos^2\alpha,$$

$$E_{\mathrm{FIN}}/\mathrm{M}_f = -0.314H_0 - 0.234|H_\sigma| + H_{\mathrm{MST}}\sin^2\alpha. \qquad (11)$$

The magnetoelastic H_σ and magnetostatic H_{MST} fields are equal here

$$H_\sigma = -1.5\lambda_{100}\sigma_i/\mathrm{M_S}, \ H_{\mathrm{MST}} = N_\perp^*\mathrm{M}_f. \qquad (12)$$

Equating the energy difference (11) to the energy of potential barriers of 90-degree DB equal to ($H_B^{90}\mathrm{M_S}$) [11,12], we obtain with $\theta_2 = 18.3^\circ$ the equation for determining the peak field of the curve $\mu_{90}(H_0)$ ($H_1 > 0$):

$$-0.635H_1 + 0.802|H_\sigma| + \cos^2\alpha H_{\mathrm{MST}} = H_B^{90}. \qquad (13)$$

A similar calculation for the field $H_2 < 0$ with a 90% transition M_f from the angle $\theta_2 = 108.3^\circ$ to the angle 198.3° gives the equation for determining the field $H_2 < 0$:

$$-0.635H_2 - 0.802|H_\sigma| - \cos^2 H_{\mathrm{MST}} = H_B^{90}. \qquad (14)$$

Equations (13), (14) differ from the corresponding equations for low-carbon steels [11,12] by the presence of a term with a scattering field. Fields H_1 and H_2 in (11), (12) are external and should be compared with those obtained from experience. Their solutions give theoretical expressions for the fields H_1 and H_2:

$$H_1^{\mathrm{THEOR}}(\theta_2 = 18.3^\circ) = 1.263|H_\sigma| + 1.57H_{\mathrm{MST}}\cos^2 - 1.57H_B^{90},$$

$$H_2^{\mathrm{THEOR}}(\theta_2 = 108.3^\circ) = -1.263|H_\sigma| - 1.57H_{\mathrm{MST}}\cos^2 - 1.57H_B^{90}. \qquad (15)$$

The introduction of the angle α in (6) takes into account the possibility of changing the direction of the light axis in C as the amount of deformation changes. With a possible change of the angle α, the relative contribution of the scattering fields to the peak fields of the curve $\mu_{90}(H_0)$ will change, as will the values of the peak fields. Using this indication it is possible to establish the very fact of a change in the light direction of the vector $\mathbf{M}_c$ with a change in the magnitude of the deformation.

Equating in the expressions (15) H_B^{90} to zero, we obtain the equations for the fields of formation of 90-degree DB H_1^{90} and H_2^{90}, which halve the grain with θ_2 in each pair of grains with LAB (as in the case of low-carbon steels [11,12]). The latter corresponds to the minimum energy of this grain.

Since there are three unknowns in two equations (15): H_σ, $H_{\mathrm{MST}}\cos^2\alpha$, H_B^{90}, they cannot be found from them simultaneously. But the form of these equations allows finding a general expression for the potential barrier field of 90-degree DB H_B^{90}:

$$H_B^{90} = [H_1(\varepsilon_{\mathrm{pl}}) + H_2(\varepsilon_{\mathrm{pl}})]/(3.14). \qquad (16)$$

It is natural to assume that the values of H_B^{90} in U8 steel with coarse-plate perlite are greater than in low-carbon steels of the type St3 [11,12] due to the braking action of a set of plates C during the displacement of 90-degree boundaries in F. However, this requires experimental values of the fields of the peaks of the curves $\mu_{90}(H_0)$.

There is only one study [17], where such measurements were carried out in U8 steel with coarse-plate perlite. However, the values of H_1 and H_2 for different values of ε_{pl} are not given in it: the authors of [17] gave only the arithmetic mean of these values (excluding the sign of the field H_2) and called them magnetoelastic fields H_σ. They did it without any physical justification, despite the fact that there is such a justification for the physical nature of the appearance of the peaks of the curve $\mu_{90}(H_0)$ (see [11,12], as well as a brief summary in the introduction to this paper in section 1). It is easy to prove the incorrectness of such a „reception" authors [17], based on the stress values they received: for example, at $\varepsilon_{\text{pl}} = 8\%$ they have $\sigma_i = -349$ MPa, as a result, the maximum value of these stresses should be is equal to $\sigma_i^m = -1047$ MPa, which is much greater than the tensile strength of this steel, equal to 760 MPa. This circumstance negates the main result of the work [17], stated by its authors.

The reason for this is that the authors did not take into account the mechanisms of formation of residual stresses (1)−(4) and features of the behavior of pairs of grains with LAB. Note that the authors of [17] took into account the method of allocating the contribution to magnetic permeability only from 90-degree transitions, developed in [11,12] (this is „subtraction" in the terminology of [17]).

Considering that there are three unknowns in the theoretical expressions for the fields H_1 and H_2 (15), in addition to the fields of the peaks of the curves $\mu_{90}(H_0)$, additional experiments are required to independently find residual stresses in these fields to determine them. As shown in [18], it is possible to obtain the maximum value of residual stresses $\sigma_i^{\max}$ from the dependence of the coercive force on elastic tensile stresses $H_C(\sigma_0 > 0)$ in steel Ct3, which, as already noted above, is three times greater than the value σ_i at the peak fields of the curve $\mu_{90}(H_0)$.

Inserting the value σ_i obtained in this way in the expressions for the fields H_1 and H_2 and equating them with the corresponding experimental values of these fields, it is possible to obtain physically justified values of the contributions of local scattering fields H_{MST}, as well as the values H_B^{90}.

The above determines the NDT method of residual compressive stresses already on structures made of steel U8 with coarse-plate perlite. To do this, on a set of samples of this steel with different deformations, it is necessary to obtain the fields of the peaks of the curve $\mu_{90}(H_0)$ and the dependencies $H_C(\sigma_0)$ for each given value of deformations, which will give us the values $\sigma_i^{\max}$ and σ_i. Taken together, these data will allow obtaining dependency curves $\sigma_i(H_1)$ and $\sigma_i(H_2)$.ds to a smaller contribution to the peak fields. Then, it is possible to immediately obtain the values of residual compressive stresses that interest us by measuring the fields H_1 and H_2 on specific U8 steel structures and comparing them with curves obtained in the laboratory on U8 steel samples.

Conclusion

1. The presence of Patch-Pitch orientation relationships between single-crystal plates F and C in U8 steel grains with residual compressive stresses leads to the appearance of magnetic charges on their interface planes, creating local magnetostatic fields H_{MST}, which do not depend on σ_i and can give a noticeable contribution to the values of the fields of the peaks of the curve $\mu_{90}(H_0)$.

2. Theoretical expressions are obtained for the fields of the peaks of the curve $\mu_{90}(H_0)$, depending on the magnetoelastic and local magnetostatic fields, as well as on the field of the potential barrier of displacements of 90-degree DBs. The structure of these expressions allows finding a common expression for the fields H_B^{90}.

3. It was found that additional experiments are necessary to find all the parameters of the theory H_σ, H_{MST}, H_B^{90} in steel U8. The dependence of the coercive force on elastic tensile stresses is proposed is proposed as such.

4. An algorithm for determining residual stresses in U8 steel structures with coarse-plate perlite is proposed.

5. The results obtained in this work allow understanding why the peak fields of the curve $\mu_{90}(H_0)$ in U8 steels with globular perlite at this deformation are always less than their values in the case of coarse-plate perlite (see these data in [10]): in the first case, due to the shape effect, the scattering fields are noticeably smaller, which ultimately leads to a smaller contribution to the peak fields.

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Conflict of interest

The author declares that he has no conflict of interest.

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