Magnetic Methods for Estimating Elastic and Plastic Strains in Steels of Different Classes

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Abstract

The majority of structural components and parts operate under complex stress conditions. Investigations into the behaviour of the magnetic characteristics of engineering materials under the action elastic and plastic strains provides a basis for monitoring loaded structural components.

Keywords: Magnetic characteristics, Elastic and plastic strains, Engineering steels

For metastable steels of the austenitic class, the relation between magnetic parameters and the stress-strain state is to a great extent governed by the formation of paramagnetic and ferromagnetic phases. Nickel-free steels based on the Fe-Mn and Fe-Mn-Cr systems are widely used at low and cryogenic temperatures as engineering materials. These steels have a sufficient safety margin and preserve high plastic properties in the low-temperature region.

However, deformational martensitic transformations lead to a considerable change not only in the microstructure of metastable steels, but also in their physical properties. Particularly, the α´-phase, as distinct from the case with austenite and ε-martensite, is ferromagnetic. In some cases, the appearance of even insignificant quantity of the α´-phase causes worse service properties of steel (corrosion resistance and required magnetic permeability), and this is indicative of the need for monitoring the quantity of strain-induced martensite.

An examination of the intensity of the ferromagnetic α´-phase formation and the change of the complex of magnetic characteristics under plastic deformation has shown that in steel 05G20S2 (C: 0.05%, Mn: 19.7%, Si: 1.48%, and the rest Fe) in the initial state the magnetization of the specimens does not exceed 4.2×10^{-4} T and that it grows monotonically as the amount of strain increases. The initial stages of deformation of steel 05G20S2 are characterized by the formation of a highly-disperse ferromagnetic phase with the particle size close to the one-dimensional state. As the amount of strain increases, the size of ferromagnetic particles grows, they change into a multidomain state, and the coercive force decreases to H_c = 27.4 kA/m.

Steel 03G21Kh13 (C: 0.03%, Mn: 21.66%, Si: 0.14%, Cr: 13.22%, and the rest Fe) even in the initial state has a rather high saturation magnetization J_{max} (fig.1a), which may be due to the presence of about 4% of δ-ferrite in the structure of hardened specimens. Under tension and compression of this steel, due to the formation of α′-martensite, magnetization grows monotonically with the amount of strain. The magnetization curves are mildly sloping, and this bears witness to the prevalence of rotation under magnetization. The coercive force also increases with the amount of strain Λ ($\Lambda = 2\sqrt{3}\cdot\ln(d_0/d_i)$ where d_0 is specimen diameter prior to deformation and d_i is specimen diameter after the corresponding deformation step), though there is a tendency for the saturation of its value at Λ>0.5, fig. 1b).

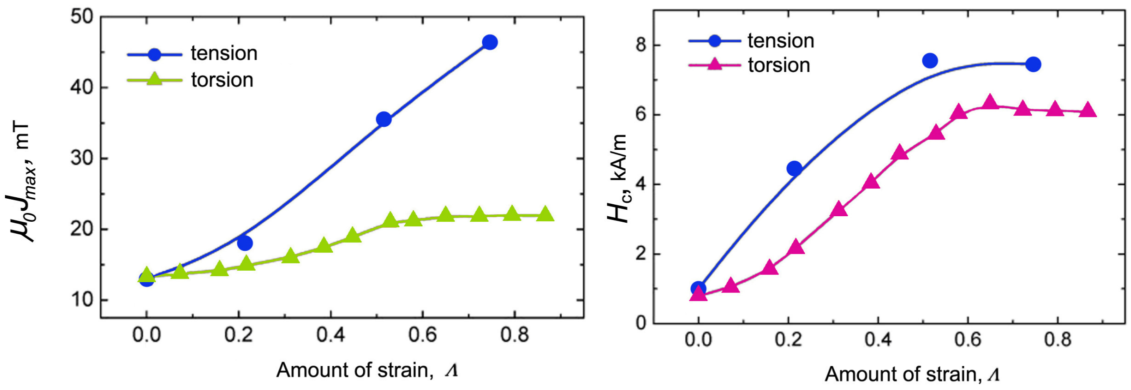

Fig.1. The effect of tensile and torsion strains on the saturation magnetization $\mu_0 J_{max}$ and coercive force H_c of steel 03G21Kh13.

An important aspect of the diagnostics of the structural condition of engineering steels operating under sustained mechanical loading is the assessment of the amount of accumulated deformation damage. There is a concept [1,2] that the value of damage $\omega=\Lambda/\Lambda_f$ (Λ_f is the amount of strain at the instant of specimen fracture) of engineering steels and alloys in the initial state is zero, and in the state immediately prior to fracture it reaches its limit value ω=1. The calculation of ω after different amounts of torsion strain made for samples of steel 03G21Kh13 has shown that the values of the coercive force on the major hysteresis loop and maximum magnetization change from accumulated damage the same way as from the amount of strain reached (figs. 1 and 2).

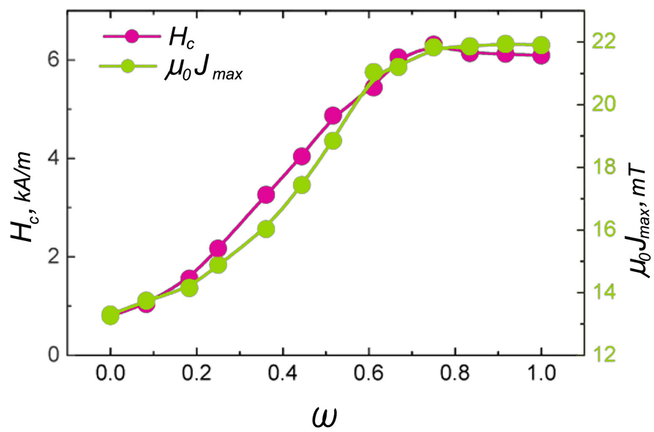

Fig.2. Coercive force H_c and saturation magnetization $\mu_0 J_{max}$ for steel 03G21Kh13 as functions of torsional damage.

It has been found that, in torsion, the region of the monotonic growth of J_{max} and H_c is in the range of strains $0<\Lambda<0.6$ and that it corresponds to the accumulated amount of deformation damage $0<\omega<0.7$, which is maximum permissible for articles, constructions and engineering structures in a long-run service. This testifies to the possibility of monitoring the condition of metastable austenitic steels by magnetic techniques in terms of the assessment of the plastic strain attained and the amount of deformation damage accumulated.

The deformation-stable steels 30G21Kh13 (C: 0.28%, Mn: 20.74%, Si: 0.14%, Cr: 4.25%, and the rest Fe) and 07G21AKh13 (C: 0.07%, Mn: 19.28%, Si: 0.29%, Cr: 13.71%, N: 0.15%, and the rest Fe), where there is no ferromagnetic phase formed under deformation, are diamagnetics (see fig. 3). However, steel 30G21Kh13 becomes paramagnetic at tensile strain over 0.55. This change is caused by the precipitation of paramagnetic particles of ε-martensite in the diamagnetic γ-matrix.

High strength and high plasticity combined enable martensite-aging steels to be widely used for making critical products. To estimate the current technical condition of these products having served under complex temperature and force actions is currently a challenge. The monitoring is based on the mechanisms of variation of magnetic characteristics under the action of stresses and strains following different loading diagrams.

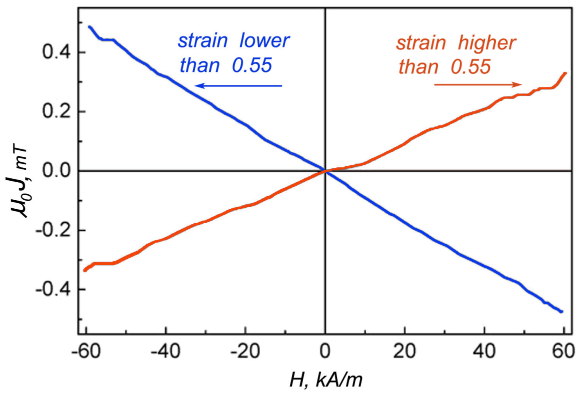

Fig.3. Magnetization reversal curves for steel 30G21Kh13 under tension.

For this purpose, the deformation behaviour of the magnetic characteristics of martensite-aging steel 03Kh11N10M2T (Cr: 108%; Ni: 9.40%; Mo: 1.97%; Ti: 0.85%; Al: 0.28%; Si≤0.15%; Mn<0.10%; the rest Fe) subjected to quenching with subsequent tempering (aging) in the temperature range between 400°C and 580°C was studied, and this has enabled different degrees of age hardening to be obtained. High tempering (620°C and 660°C) results in a two-phase ($\alpha+\gamma$)-structure containing, respectively, up to 45 and 22 % of reverted austenite obtained in the material. The magnetic properties of the specimens were measured directly in the course of loading.

The deformation behaviour of the magnetic characteristics of steel EP678 under tension (fig. 4) is discussed in view of internal stresses, the structural condition and phase stability of the material. It is demonstrated that, after tempering in the range between 400°C and 580°C, the deformation behaviour of magnetic characteristics is governed mainly by the size of intermetallide particles and the level of microstresses. After high tempering, the main factor influencing the variation of magnetic characteristics in loading is the deformational $\gamma\rightarrow\alpha$ transformation. The nonmonotonic behaviour of the coercive force H_c under tension in the region of stresses below $\sigma_{0.2}$ is represented as resulting from the positive magnetoelastic effect and the presence of second-phase particles in the structure. The former decreases H_c, and the latter decelerates this decrease; the coarser the intermetallide particles precipitating during aging, the more intense is the deceleration.

The correlation curves obtained testify to the feasibility of assessing the amount of strain and current metal damage by magnetic measurements and predicting the residual life of articles by these data.

The mechanisms of the deformation behaviour of the magnetic characteristics of low- and medium carbon steels have been studied on all the portions of the stress-strain diagram up to necking, under plane stress condition in elastic-plastic tensile deformation.

In order to analyse the behaviour of the coercive force in tension, the "H_c versus amount of strain" curves were superposed on the corresponding stress-strain diagrams (fig. 5). Three characteristic portions are obvious in the behaviour of the coercive force, namely, 1) the region of elastic strain; 2) the yield plateau and/or drop; 3) the region of developed plastic strain.

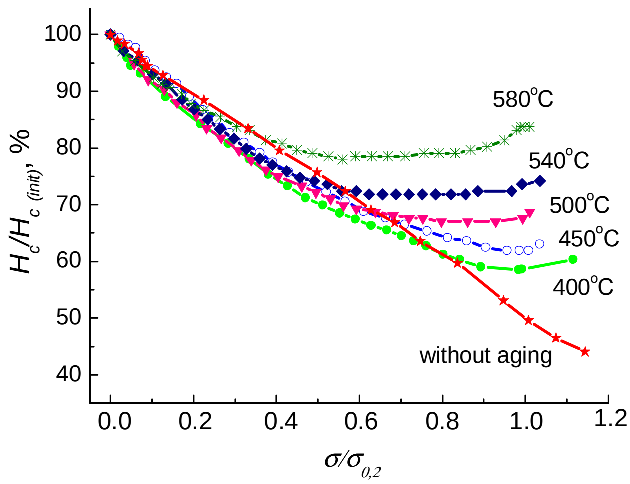

Fig.4. A relative change in the coercive force as a function of specific elongation of specimens quenched from 920°C with subsequent aging in the temperature range between 400°C and 580°C.

The experimentally obtained nonmonotonic dependence $H_c(\varepsilon)$ in the region of elastic stresses (fig. 5a′, b′) can be represented as resulting from the effect of a number of factors. Particularly, the tension of specimens in the elastic region leads to the formation of a magnetic texture (induced magnetic anisotropy)[3]. If there is a positive magnetoelastic effect (magnetostriction and external stresses of the same sign), the magnetic moments are oriented along the stress axis, and, under magnetization along the direction of tension, the coercive force decreases and magnetic permeability grows. However, the magnetostriction of iron may change its sign under further loading[4,5], and this causes a negative magnetoelastic effect and changes the type of magnetic texture. Besides, the "sign" of the magnetoelasic effect can be determined by the second magnetostriction constant λ_{111}, which is negative in crystallites of iron and iron-carbon alloys. Affected by these factors, the coercive force will grow.

In the range of stresses between the upper yield stress and the lower one, i. e., on the portion corresponding to the yield drop and/or plateau, the coercive force behaves nonmonotonically (fig. 5a, b). The effect of stresses reaching and exceeding the value $\sigma_{0.2}$ leads to the collapse of the magnetic texture of stresses[3], and the main factor affecting the coercive force in the plastic strain region is the increase in the density of dislocations and dislocation clusters (H_c~$N^{1/2}$ where N is dislocation density[6]) and the formation of a crystallographic strain texture.

The peculiarities of the variation of magnetic characteristics near and on the yield drop and yield plateau portion call for a more detailed discussion. As the stress $\sigma_{0.2}$ is approached, the coercive force of all the specimens tested grows significantly, the most active growth of H_c being observed prior to $\sigma_{0.2}$ rather than at $\sigma_{0.2}$, which agrees with earlier results[7]. In steel St3 the coercive force stops growing as soon as it reaches the upper yield stress, the value of H_c remains constant or slightly decreases, and then, after passing the lower yield stress, it resumes growing, though less intensively (see fig. 5a). The yield drop on the tension diagram is known[8] to result from the separation of dislocations from Cottrell atmospheres upon reaching the critical stress. The dislocation density does not increase in this case, and it can even decrease in some cases, since some of the dislocations emerge to the specimen surface and form Chernov-Luders bands.

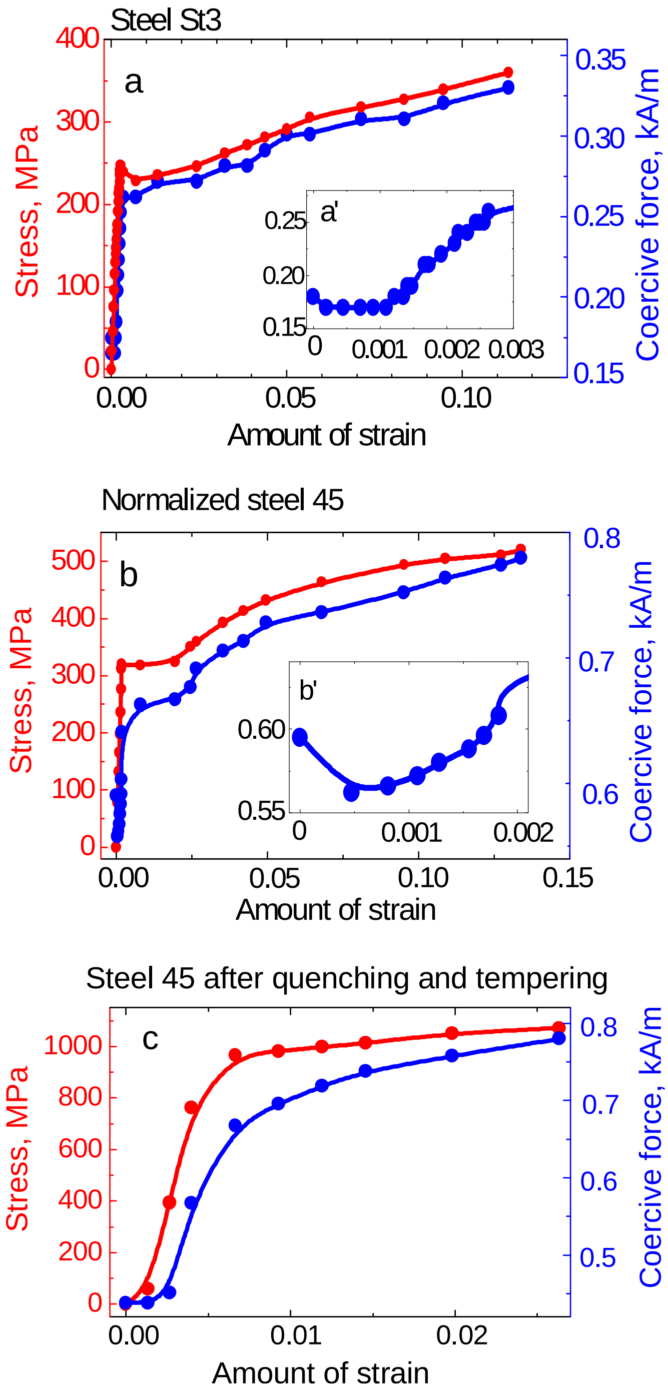

Fig.5. Tensile stress and coercive force as dependent on the amount of strain for carbon steels st3 (C~0.03%), 45 (C~0.45%).

The investigation has offered a technique to restore the stress-strain diagrams for homogenous steel products by coercive force and/or residual induction, and this is a basis for magnetic monitoring the stress-strain state of loaded components of steel structures.

To test nondestructively the condition of the constituents of a multilayer product and to assess their residual life, it is suggested that, as was proposed earlier[9], the value of the field of maximum differential magnetic permeability $H_{\mu d max}$ of the magnetically soft and magnetically hard constituents of a compound product should be used as an informative parameter. A method for calculating the stress-strain diagram of a flat two-layer steel product under uniaxial tension from the strain-dependences of the magnetic characteristics of the constituents was proposed[10], the dependences being obtained directly in the course of loading.

Figure 6a shows the major hysteresis loops of compound specimen No.1 see the table) and its constituents No. 2 and No. 3 (measured separately), as well as the corresponding field dependences of maximum magnetic permeability in the initial state (before loading). The hysteresis loop of compound specimen No. 1 (curve 1 in fig. 6a) has a form characteristic of two-layer ferromagnetic[9], and it differs from hysteresis loops for homogeneous materials (curves *2* and *3*), among other things, in that they have two bends. One of them, localized in the region of smaller fields, corresponds to the magnetically soft component, the other – to the magnetically hard one. The mechanism of the formation of these bends was discussed earlier[6,9]. On the field dependence of differential magnetic permeability bends of the kind manifest themselves as maximums (peaks) of differential magnetic permeability (fig. 6b). The number of peaks corresponds to the number of layers with different magnetic hardness, the peak height proportion being determined, in particular, by the proportion of the thickness of the respective layers[6, 9].

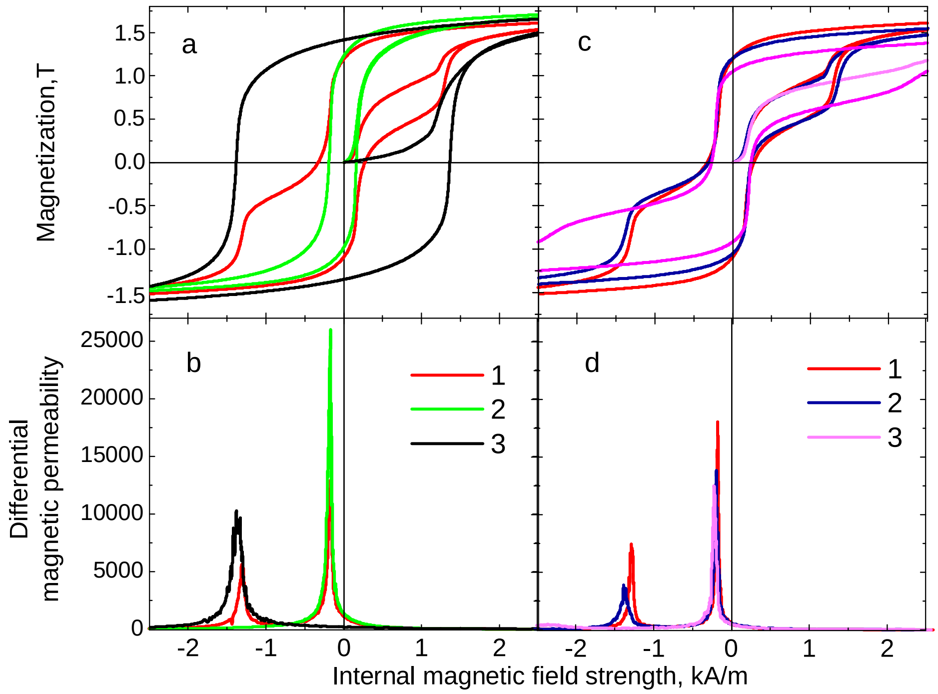

Fig.6. The major magnetic hysteresis loops for compound specimen No. 1 (curve 1) and its components (curves 2 and 3) (a) and the corresponding field dependences of differential magnetic permeability (b) in the initial state; for the compound specimen in the initial state (curve 1) (c), under external stresses amounting to 0.5 of the fracture stress of the magnetically hard component (2) and immediately before the fracture of the magnetically hard component (3).

Table. The geometric dimension of the test parts of the specimens and their magnetic characteristics in the initial state

№	Specimen	Dimensions, mm	H_c , kA/m	B_r, T
1	compound specimen No. 1: St3 + 45 (quenching + tempering)	90 × 20 × (2.14+1.10)	0.30	1.14
2	St3 (annealing) (C: 0.03 %; Fe: the rest)	90 × 20 × 2.04	0.18	1.11
3	45 (quenching + tempering) (C: 0.45 %; Fe: the rest)	90 × 20 × 1.20	1.36	1.37

Figure 6c, d shows a change in the form of the field dependences of differential magnetic permeability and the evolution of the major hysteresis loops of compound specimen No 1. To avoid complication of the figures, they show curves fitting only three points of the stress-strain diagram, namely, curves *1* correspond to the initial state, curves *2* are taken under external stresses amounting to 0.5 of the fracture stress of the magnetically hard component, curves *3* being obtained immediately before the fracture of the magnetically hard component. It follows from fig. 6c, d that in the course of deformation the peak of the magnetically hard component on the field dependence of the differential magnetic permeability shifts into the region of stronger fields and, besides, it becomes less intensive and more widened. The peak of the magnetically soft component also shifts into the region of stronger fields, due to the small absolute shift magnitude (as compared to that for the magnetically hard component), this shift is less noticeable on the field dependence. The bends of the major loop also shift into the region of stronger fields (see fig. 6c).

Thus, the field dependences of differential magnetic permeability determined by differentiating the descending branches of the corresponding hysteresis loops with respect to the field reveal the maximums (peaks) of differential magnetic permeability of separate layers in two-layer products.

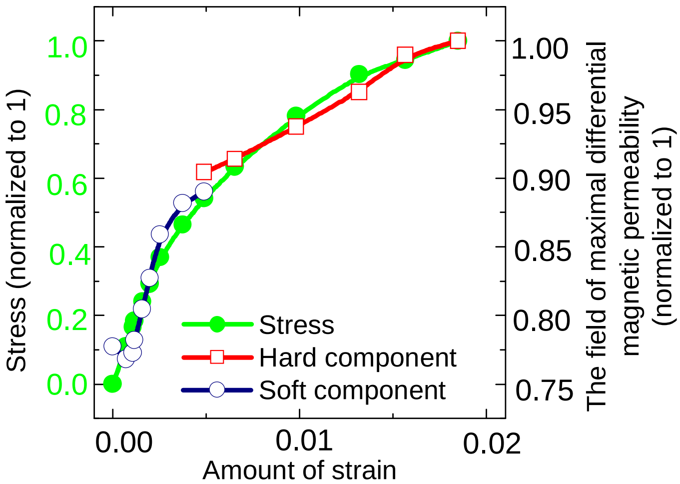

Fig.7. Tensile stress and the field of differential magnetic permeability as dependent on the amount of strain for a two-layer product.

The characteristics of the peaks of differential magnetic permeability (peak field, height and width) are shown to vary naturally under elastic and plastic strains, therefore they can serve as tool for testing the condition of multi-layer products. Figure 7 shows a procedure of restoring the stress-strain diagram (green curve) of a two-layer product by its magnetic characteristics. The procedure is based on the following mechanism: in the tension of a two-layer product, a sharp increase in the value of the field of maximal differential permeability of each component occurs under the effect of strains corresponding to the yield stress of this component. This enables the deformation curve for a two-layer product to be restored – the field $H\mu_{dmax}$ of the magnetically soft component is the most informative in the earlier stages of deformation (fig. 7 (o)), whereas $H\mu_{dmax}$ of the magnetically hard component is the most informative at higher amounts of strain (fig. 7 (□)).

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