APPLICATION OF MAGNETIC METHODS FOR STRUCTURAL-PHASE ANALYSIS AND EVALUATION OF ARTICLE SERVICE LIFE

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In different stages of a product-making process including forming, machining and thermal treatment, as well as in use, the material of an article suffers structural changes and phase transformations. To estimate the structure and phase composition of products and to determine their physicomechanical properties, magnetic methods of nondestructive testing are widely used, which lately have started to be applied to identify any changes in these properties of machine parts and structural components while they are in use.

The use of magnetic properties for estimating the structural state and strength characteristics of products is based on much the same effect of structural factors on magnetic and mechanical properties. Studying the effect of different structural parameters on the retardation of sliding dislocations and the inhibition of domain wall motion, one can note some similarity in the effect they have on the mechanical and magnetic properties. For instance, higher dislocation density (N) in the steel structure is accompanied by higher strength characteristics and coercive force values. Note that the conventional yield stress $\sigma_{0.2}$ and the coercive force H_c are proportional to $\sqrt{N}$. A higher level of microstresses in steel causes higher values of $\sigma_{0.2}$ and H_c. A greater volume (V_p) of the pearlitic component in the steel structure is accompanied by higher values of H_c and $\sigma_{0.2}$. For lamellar pearlite, $H_c \sim V_p$; for granular pearlite $H_c \sim V_п^{2/3}$, whereas $\sigma_{0.2}$ is independent of pearlite form ($\sigma_{0.2} \sim V$). An increase in the average grain size (d_{av}) is followed by a decrease in both $\sigma_{0.2}$, and H_c (yet, $H_c \sim 1/d_{av}$, and $\sigma_{0.2} \sim 1/\sqrt{d_{av}}$.

The effect of structural factors can be vividly illustrated by the domain structure in polycrystalline ferromagnets taken as an example, which depends largely on the size of the grains and their mutual orientation. Grain size and disorientation have a certain effect on the magnetic domain structure, domain wall mobility and, hence, many magnetic characteristics, including separate acts of irreversible change of magnetization – Barkhausen jumps. Theoretical and experimental investigations into the relation between the average grain size in ferromagnetic steel and magnetic characteristics of the material (coercive force, domain structure parameters, information parameters of the Barkhausen effect etc.) have become classical problems of the physics of magnetic phenomena and magnetic structuroscopy.

In the general case the width and length of magnetic domains are governed by polycrystal grain size. Figure 1 illustrates a typical heterogranular macrostructure of a polycrystal of the alloy Fe−3% Si, where the orientation of the grain surface contains a crystallographic component of texture (110). It is obvious that greater average grain size corresponds to wider strip 180° domains.

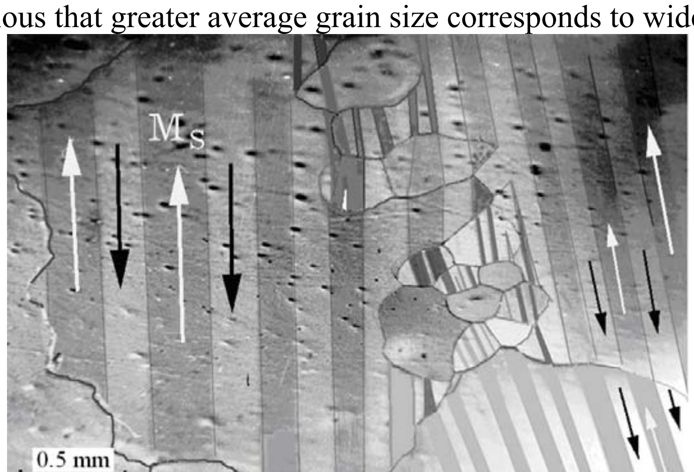

Fig. 1. The domain structure in a polycrystal of silicon iron with a multicomponent crystallographic structure

Depending on the conditions of metal processing (thermal treatment, plastic deformation), grain size and disorientation may range widely. The study of the laws of the relations of magnetic properties to the structure of cold- and hot-deformed steels after different annealings has enabled us to suggest that magnetic methods should be applied to estimate the structural state and mechanical properties of rolled stock. At numerous metallurgical plants of Russia products for a long time have been checked out with the application of magnetic nondestructive testing devices.

In many instances the changes occurring in the structure and phase composition of steel during quenching and tempering have an adequate effect on magnetic and mechanical properties, therefore the structural state and mechanical characteristics of steels after quenching and tempering are also universally estimated with the application of magnetic methods.

Modern mechanical engineering employs magnetic methods to solve the following problems [1 – 3]:

- determination of the structural state and mechanical properties of cold- and hot-rolled stock both at the producer's and consumer's sites (outgoing and incoming quality control);
- inspection of the structural state and strength characteristics of thermally treated steel and cast-iron products (annealing, normalization, quenching, tempering, and aging);
- determination of the phase composition and porosity, detection of paramagnetic and ferromagnetic portions with different physical and hence mechanical properties in cast, cermet products and welds;
- inspection of the structure, physicomechanical properties and thickness of layers surface-hardened by different methods (induction hardening, thermochemical treatment, strengthening by concentrated energy fluxes, vibration strengthening, decarburization in steel and chilling in cast iron);
- estimation of the stress-strain state and its changes in materials after thermal treatment and plastic deformation and in structures while in use;
- detection of a crystallographic texture, anisotropy of mechanical properties before forming or after plate and sheet deformation;
- steel grading, qualitative assessment of the content of principal alloying constituents.

The methods and facilities for magnetic structural-phase analysis can only be used when the relations of the magnetic properties of steels to their structural state and phase composition (and hence mechanical properties) after different strengthening and softening treatments are clearly known [1, 2, 4]. The knowledge of these relations enables the current body of mechanics to be applied to the evaluation of the life of structural members and thus to estimate their actual technical condition.

The promotion of nondestructive testing methods as applied to checking the quality of annealing is preceded by investigations focussed on the establishment of a correlation between magnetic parameters (e.g., H_c) and those to be inspected (most commonly mechanical), and by the assessment of how they are affected by various technological factors governing the actual coefficient of this relation for specific conditions of rolling. (When magnetic nondestructive testing methods are applied in order to take into account specific features of a production process, statistical data are collected and processed at the plant.)

Also, the structural state and mechanical properties of metals change during thermal treatment. Nondestructive magnetic methods are successfully applied to inspect the quality of quenching [1, 2, 4, 5]**.** The appearance of martensite in the structure of steel during quenching is accompanied by increased effective magnetic anisotropy ("magnetic rigidity") arising from the tetragonality of the martensite lattice, higher dislocation lattice and the level of microstresses; at the same time the area of magnetic hysteresis loops grows significantly and the coercive force grows more than twice (Fig. 2). Saturation magnetization M_s represents the changes occurring in the phase composition of the steel, therefore lower M_s is due to the appearance of residual austenite in the structure of quenched steel (Fig. 2).

Hypereutectoid steels have the same laws of the variation of magnetic and electrical properties as hypoeutectoid ones at low austenization temperature, whereas in the region of superheat quenching temperatures, there is some difference, namely, ambiguous quenching temperature dependence of the coercive force for hypereutectoid steels (Fig. 2b). The structures and strength properties corresponding to low austenization temperature (underheating in quenching) can be detected by any magnetic characteristic.

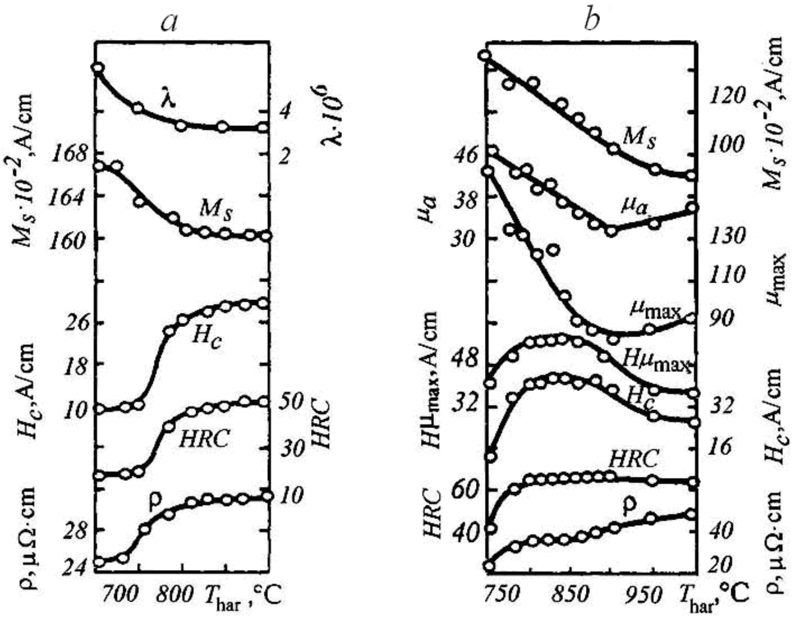

Fig. 2. The physical properties of steels 34KhN3M (a) and ShKh15 (b) as dependent on quenching temperature.

The superheating of hypoeutectoid steels cannot be detected by magnetic and mechanical characteristics, whereas for hypereutectoid steels it is proposed that superheating can be detected by two parameters, namely, coercive force and saturation magnetization.

Structural transformations and the effect they have on the strength characteristics of steels in tempering can also be evaluated with the use of magnetic characteristics [1, 2, 4, 5]. Engineering steels with less than 0.3 % carbon content are characterized by a monotonic variation of the majority of physical properties and strength characteristics in the range of tempering temperature between room temperature and 650°C, Fig. 3a. The monotonic variation of magnetic characteristics with tempering temperature, which is due to the isolation of hydrogen from the hard solution, austenite decomposition and a lower level of microstresses, allows their use for the nondestructive inspection of the structural state and the strength properties of products tempered at temperatures ranging between 150 and 650°C.

For engineering steels with 0.3 % and higher carbon content, the variation of magnetic properties at high tempering temperatures is not monotonic, Fig. 3b. Since many steels of different classes, which are now commonly used in modern mechanical engineering for making separate machine parts, units and mechanisms, contain, as a rule, more than 0.3 % of carbon, there is a challenge of testing components made of these steels. Since the majority of magnetic characteristics commonly used in nondestructive testing vary ambiguously with tempering temperature, they cannon be used to inspect medium- and high-temperature tempering of products made of steels of this group.

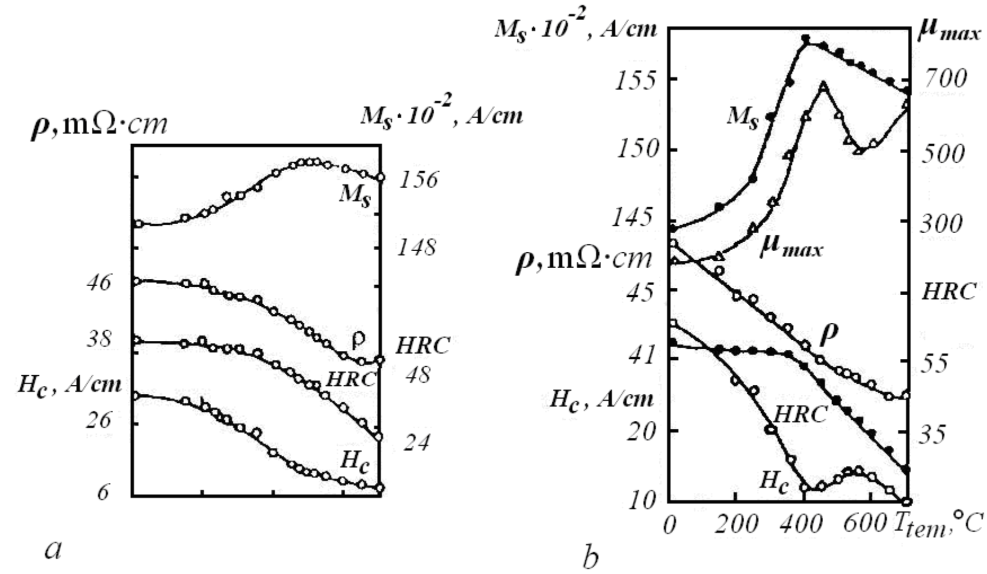

Fig. 3. Physical properties of steels SP28 (a) and ShKh15 (b) as dependent on tempering temperature.

Proceeding from the analysis of the resistance of magnetic states to the effect of electromagnetic fields, it is possible not only to inspect the quality of quenched and tempered steels, but also to diagnose changes in the physicomechanical properties of products while in use.

Magnetic methods can be instrumental for solving special problems. For example, it is proposed that the wear resistance of thermally hardened drill bits made of steel U8A can be tested by measuring the coercive force (H_c). It was found that micromachining is the dominant wear mechanism and that the wear resistance grows linearly as carbon content in martensite rises to 0.9 %. The coercive force of quenched steels in its turn grows linearly as carbon content in martensite rises to 0.8 %. Similar martensite carbon content dependences of the coercive force and wear resistance for quenched steels, as well as the high sensitivity of the both characteristics to the presence of carbon (up to 0.8 mass %) in the α-hard solution, serve as a physical basis for the applicability of magnetic technique to estimating the abrasive wear resistance of steels with carbon content not higher than 0.8 %.

A vital issue for the science of materials is to obtain optimal metal structures with the level of microstresses not exceeding a certain critical value at which cracks appear. Therefore the level of residual stresses in structures and the value of microstresses in a material are important for the life cycle of a product. The nondestructive determination of the level of internal stresses is a challenge, therefore it attracts the attention of numerous researchers.

The study of the effect of elastic-plastic deformation on the magnetic properties of alloys and steels testifies that, to estimate elastic-plastic strains, hysteresis loop parameters can be used, e. g., coercive force, as well as different kinds of magnetic permeability.

Lately some achievements in estimating the level of microstresses have surfaced in the context of intensive investigations into fairly new phenomena (acoustic manifestation of the Barkhausen effect, magnetoelastic acoustic emission (MAE) and electromagnetic acoustic transformation), whose nature is associated with the occurrence of elastic vibrations resulting from local acts of magnetostrictive deformation when 90^0 domain walls displace irreversibly.

Examination of the effect exerted by elastic and plastic strains in single crystals of silicon iron, nickel and in steels on magnetoelastic acoustic emission bears witness to the sensitivity of MAE parameters to uniaxial tensile and compressive stresses. Moreover, using acoustic and electromagnetic manifestation of the Barkhausen effect, one can find the value and sign of elastic strain in ferromagnetic materials. MAE parameters are highly sensitive to variations in the level of microstresses in thermally treated and plastically deformed steels. Figure 4 illustrates root-mean-square voltage U_{MAE} as dependent on the level of internal stresses of thermally treated (Fig. 4a) and plastically deformed (Fig. 4b) steels.

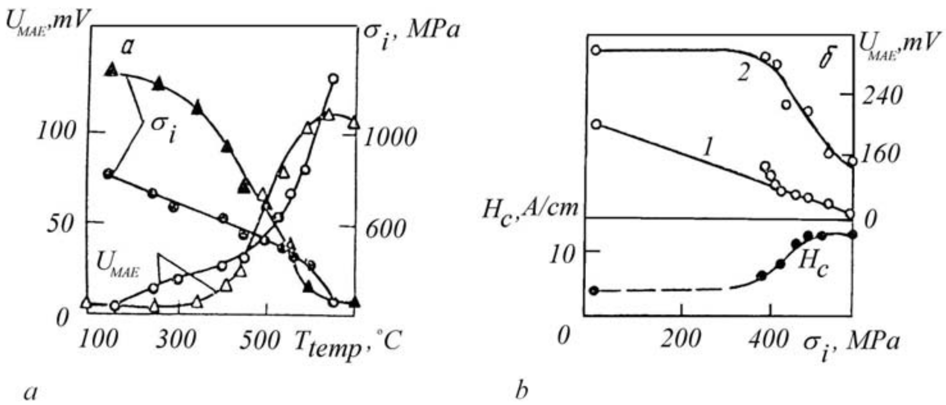

Fig. 4. The root-mean-square voltage of MAE signals and internal microstresses as dependent on the tempering temperature for steels 34KhN3M (◦, •) and 60S2A (Δ, σ) (a); the root-mean-square voltage of MAE signals and the coercive force as dependent on internal stresses (b): H^{-} = 16 A/cm (1); 48 A/cm (2).

For austenitic steels, the relation of magnetic parameters to the stress-strain state is largely determined by the formation of paramagnetic and ferromagnetic phases. The deformation-stable steels 30G21Kh13 (C=0.28%, Mn=0.74%, 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 no ferromagnetic phase is formed under deformation, are diamagnets (Fig. 5). However, the steel 30G21Kh13 becomes paramagnetic at tensile strains higher than 0.55, whereas in torsion it remains diamagnetic in the entire range of strains studied. This change is most likely to be caused by the precipitation of paramagnetic particles of ε-martensite in the diamagnetic γ-matrix. In torsion, we failed to reveal this transformation in the whole range of strains studied, as the volume of transformation products localized in the near-surface layer is rather insignificant, and the specimen retains its diamagnetic properties.

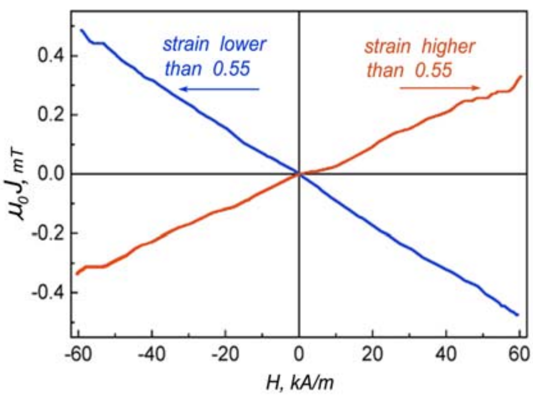

Fig. 5. Magnetization reversal curves for steel 30G21Kh13 under tension.

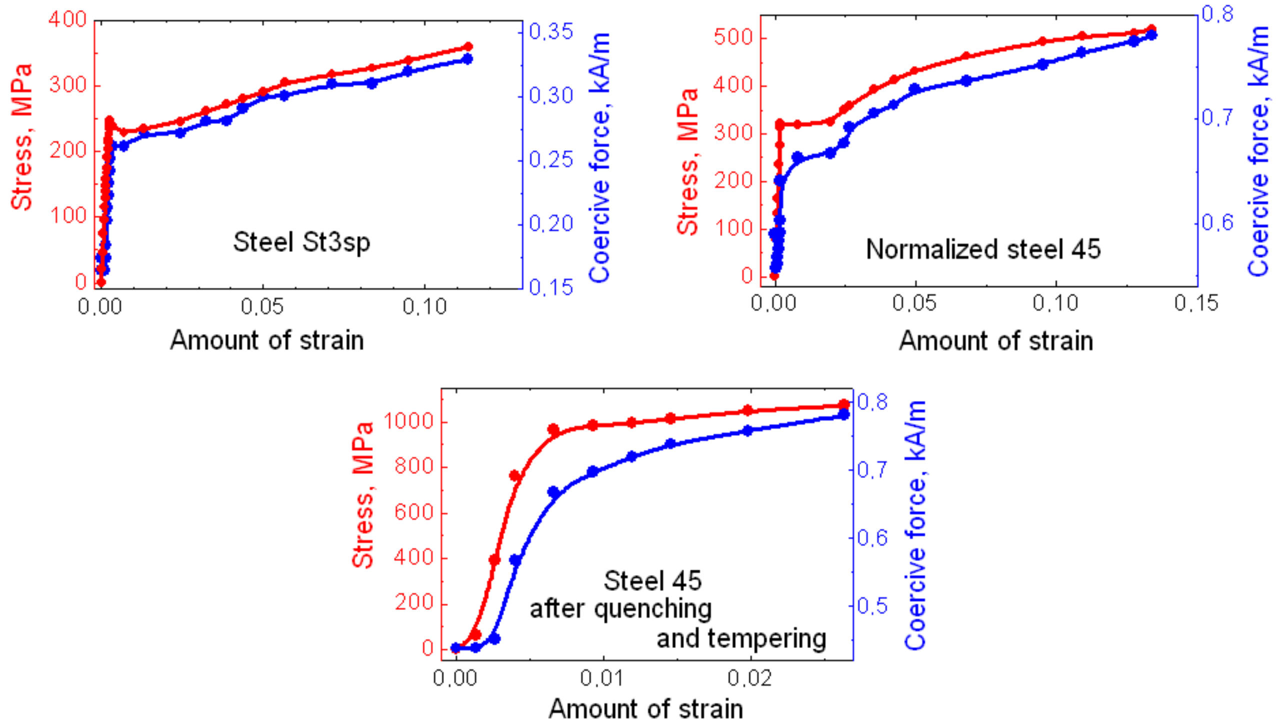

Fig. 6. Tensile stress and coercive force as dependent on the amount of strain for carbon steels.

To analyze the behaviour of the coercive force in tension, strain dependences of H_c were superposed on the corresponding stress-strain diagrams (Fig. 6). In the behaviour of the coercive force there are three distinct characteristic portions: 1) the region of elastic strain; 2) the yield plateau and/or sharp yield point; 3) the region of developed plastic strain.

In the region of elastic stresses the experimentally obtained nonmonotonic dependence $H_c(\varepsilon)$ can be represented as resulting from a number of effects. Particularly, specimen tension in the elastic region leads to the formation of a magnetic texture (induced magnetic anisotropy) [6]. In the instance of a positive magnetoelastic effect (magnetostriction and external stresses are of the same sign) magnetic moments are oriented along the stress axis, and, in magnetization along the tension direction, the coercive force decreases and magnetic permeability grows. However, as the loading proceeds, the magnetostriction of iron may change its sign, thus causing a negative magnetoelastic effect and changing the magnetic texture type. Besides, the "sign" of the magnetoelastic effect can be determined by the second magnetostriction constant λ_{111}, which is negative in iron and iron-carbon alloy crystals. Under these effects the coercive force will grow.

In the stress range between the upper and lower yield stress, i. e., on the portion corresponding to the sharp yield point and/or yield plateau, the coercive force stops growing, and it resumes growing on passing this portion. The effect of stresses reaching and exceeding $\sigma_{0.2}$ causes a collapse of the magnetic texture of stresses, and the main factor influencing the coercive force in the region of plastic strain is the increase of dislocation density and dislocation clusters (H_c~$N^{1/2}$, where N is dislocation density [6]) and the formation of the crystallographic texture of strain.

The peculiarities of changes in magnetic characteristics near and on the sharp yield point and the yield plateau need a more detailed discussion. As the stress $\sigma_{0.2}$ is approached, the coercive force of all the specimens grows significantly, the more rapid growth of H_c being observed prior to $\sigma_{0.2}$, rather than at $\sigma_{0.2}$, and this agrees with the results found in [7]. In steel St3 the growth of the coercive force is suspended as soon as the upper yield stress is reached, H_c remains constant or decreases a little, and then, after the lower yield stress is passed, it resumes growing, though less rapidly (see Fig. 5a). The sharp yield point on the tension diagram is known [8] to be attributed to the fact that the dislocations are freed from the Cottrell atmospheres when a critical stress is reached. In this case, dislocation density does not grow, and may even decrease in some cases, as some of the dislocations crop out at the specimen surface and form Chernov-Luders bands.

The results of the study enable us to propose a technique of restoring the stress-strain diagrams for homogeneous steel products by the coercive force and/or remanent induction, which cab serve as a basis for monitoring the stress-strain states of stressed structural steel members by magnetic methods.

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