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COERCIVE FORCE OF LOW-CARBON STEELS DURING ELASTIC AND PLASTIC TENSILE DEFORMATION

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Dependences of the coercive force of samples of St3-grade steel (with chemical composition Fe–0.324C–0.187Si–0.457Mn–0.026Cr–0.029Cu–0.008Co*) during elastic and plastic tensile deformation are investigated. It is demonstrated that in the region of small deformations, plastic deformation is non-uniform over the length of the operating part of the sample. For well-annealed steel, the dependences of the coercive force on the elastic sample deformation became reversible, and for plastically deformed steel, a hysteresis is observed that increases with the degree of plastic deformation of the samples. Possible reasons for the hysteresis of the dependence of the coercive force on the elastic cyclic tensile deformations are discussed.*

Keywords: carbon steel, elastic and plastic deformations, coercive force.

It is well known that while in service, carbon steel articles experience not only elastic, but also plastic deformation and often both deformation types simultaneously. Each of the deformations influencing the magnetic properties of steels has its own peculiarities. In addition, it has been revealed recently that for elastic deformations e_{el}, a hysteresis is observed in the dependences of the coercive force $N_c(e_{el})$ of plastically deformed carbon steels, namely, the dependences $N_c(e_{el})$ under cyclic loading and subsequent unloading of the sample have the form of a closed loop [1]. These circumstances complicate the identification of stress-strain states of steel articles by magnetic, in particular, coercimetric methods.

In the literature there are a lot of works devoted to investigation of the influence of uniaxial elastic and plastic deformations on the coercive force of carbon steels (for example, see [2–5]). At the same time, works in which the hysteresis in the dependences $N_c(e_{el})$ would be considered upon elastic deformation are virtually absent. In the present work, on an example of the well studied St3-grade steel (with chemical composition Fe–0.324C–0.187Si–0.457Mn–0.026Cr–0.029Cu–0.008Co), an attempt is made to model possible combinations of elastic and plastic tensile deformations and to study their influence on the magnetic hysteresis properties of the steel.

Investigations were performed on a disrupted sample of the St3-grade low-carbon steel. The operating part of the sample had a length of 50 mm and cross section of 14.1×5.3 mm^2. A virgin sample was annealed in vacuum at a temperature of 1000°C for 1 h with subsequent slow cooling. Uniaxial tension in the elastic region and plastic deformation of the sample were performed on a standard tension-testing machine in the quasi-static regime with velocity of 0.02 mm/min. To measure the deformation, a small inductive linear displacement pickup (tensometer) with the base $l_0 = 12$ mm was placed in the middle of the operating part of the sample. If necessary, linear displacement pickups were placed on the opposite sides of the operating part of the sample. The sensitivity of the tensometer with an inductive displacement pickup was 1 μm. From the measured absolute deformation, the *true* relative deformation $e = \ln(l/l_0)$ was calculated, where l_0 and l are the sample lengths at the pickup base before and after deformation, respectively.

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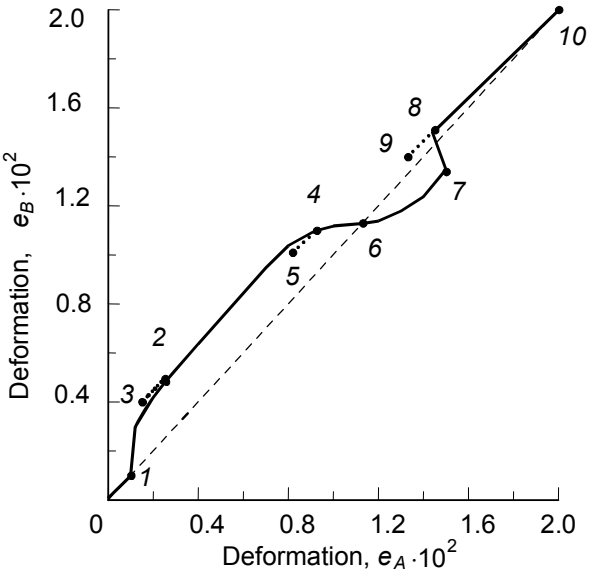

Fig. 1. Indications of deformation pickups *A* and *B* placed on two sides of the operating part of the sample during elastic and plastic deformations of the St3-grade steel: points *1*, *2*, *4*, *6*, *7*, *8*, and *10* were registered during tension; and points *3*, *5*, and *9* were registered after removal of loading.

The coercive force N_c of the operating part of the sample was measured along the direction of load application using a digital KRM-TS coercimeter with a small attached pickup. The sizes of the magnetic pole of the attached pickup were 15 × 3 mm, and the distance between the internal edges of the poles was 9 mm. The coercimeter was tuned at a clearance of 0.2 mm between the sample and the magnetic core of the attached pickup and was graduated in A/cm. The relative error in measuring the coercive force did not exceed 3 %. During loading and unloading, short-term fixing of the stress was performed under preset levels of loading to measure the coercive force and the deformation of the sample.

Measurement of the coercive force of a plastically deformed sample has some special features due to the local character of N_c measurement by the attached pickup (the length of the data pickup region was about 15 mm) and inevitable non-uniformity of the plastic flow over the length and cross section of the operating part of the sample at the initial stage of its plastic deformation. This is illustrated by Fig. 1 which shows variations of the relative deformations e_A and e_B in the limits from 0 to 0.02 fixed by the displacement pickups *A* and *B* placed on the opposite sides in the middle of the operating part of the sample during its tension.

In the initial section of the curve in the region of elastic deformation (to point *1*), indications of both pickups change synchronously with increasing *e*. Then indications of the pickup *B* start to advance indications of the pickup *A* for a sufficiently wide range of deformations. Visual examination of the sample surface at point *3* (after removal of loading at point *2*) demonstrated that on the side of arrangement of the pickup *B*, the material started to flow, and one of the Chernov–Lüders bands was located directly under the pickup *B*. In this case, the material under the pickup *A*, placed on the other side of the operating part of the sample, was still in the elastic region of deformation (without Chernov–Lüders bands). Exactly this explains the sharp change of indications of the pickup *B* in comparison with the pickup *A*. During subsequent deformation of the sample (section of the curve between points *2* and *4*), almost synchronous changes of indications of the deformation pickups are observed. Then, when the plastic flow of the material from the pickup *A* reaches the region of measurement of the pickup *B*, its indications first reach and then start to advance indications of the pickup *B* (sections of the curve between points *4*, *6*, and *7* in Fig. 1). In sections *7–8–10*, indications

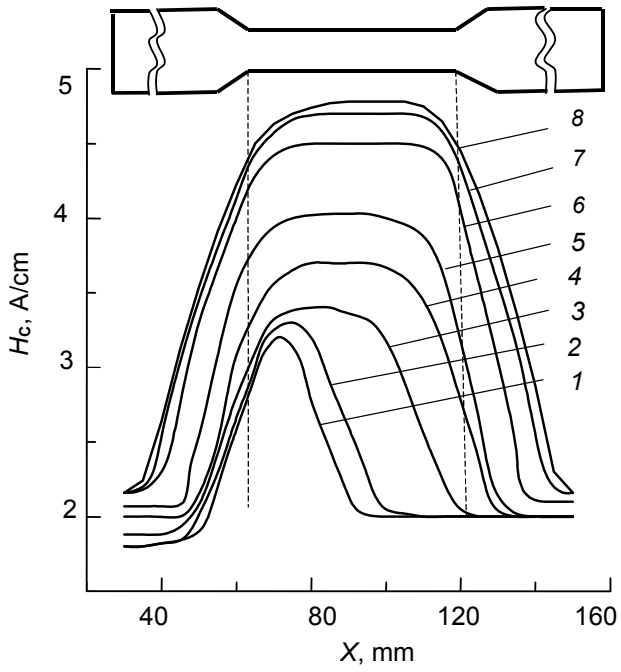

Fig. 2. Distribution of the coercive force N_c over the length of a plastically deformed sample with residual deformation $e_d \cdot 10^2 = 0.28$ (curve *1*), 0.92 (curve *2*), 1.37 (curve *3*), 1.87 (curve *4*), 3.17 (curve *5*), 5.63 (curve *6*), 8.47 (curve *7*), and 11.1 (curve *8*).

of the pickups are leveled, and starting from point *10*, a uniform plastic deformation of the sample material is observed under both pickups. The uniformity of deformation of the material in the examined part of the sample is also confirmed by observations of the Chernov–Lüders bands: they propagate from one end of the operating part of the sample, and at point *10* encompass already both sides of the measurement part. The uniformity of plastic deformation under pickups is also retained with further tension of the sample. The non-uniform character of plastic deformation in the initial stage is confirmed by measurements of N_c in the local regions located along the sample that experience different degrees of plastic deformation.

Figure 2 shows the distribution of N_c across the sample length from the operating part of the sample where the plastic deformation started. Curve *1* is drawn for the sample whose plastic deformation corresponds to point *3* in Fig. 1. Since the coercimeter measures the coercive force averaged over the cross section of the sample, the value $N_c = 3.2$ A/cm maximum for the given case was observed in the region where the plastic deformation of the material started. With increasing loading, the plastic deformation gradually extends both along the sample length and cross section, which is accompanied by an increase in N_c in other regions of the operating part of the sample. Thus, curve *2* in Fig. 2 corresponds to the relative residual deformation $e_d \approx 0.008$ (point *5* in Fig. 1). The Chernov–Lüders bands extend toward the second half of the sample encompassing the region of deformation measurement by deformation pickups from both sides of the sample. Curve *3* in Fig. 2 corresponds to the residual deformation $e_d \approx 0.0137$ (point *9* in Fig. 1). At this moment, the Chernov–Lüders bands reached the other end of the operating part of the sample. With further loading, the plastic deformation of the operating part of the sample becomes already uniform. In this case, the increase in the dislocation density causes N_c of the sample to increase (curves *4–8* in Fig. 2). From this it follows that the magnetomechanical characteristics of the St3-grade steel samples must be measured under relative deformations $e > 0.02$, since under these conditions the plastic deformation becomes uniform over the length and cross section of the sample and hence, adequately determines the average values of both plastic deformation and coercive force of the operating part of the sample.

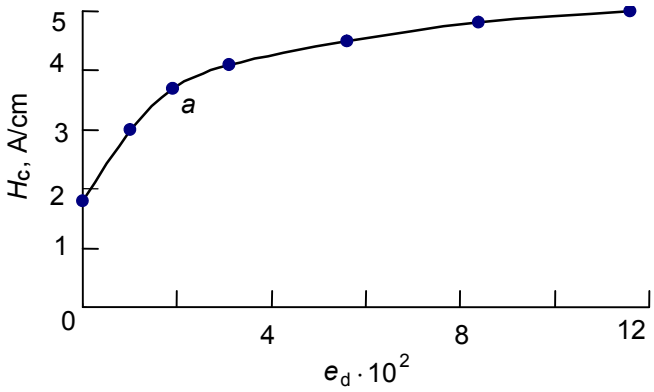

Fig. 3. Dependence of the coercive force on the residual plastic deformation for the St3-grade sample.

The process of plastic deformation of the sample and measurement of its deformation parameters in the elastic region were performed as follows. The sample was expanded up to the desired maximum e_m in the region of plastic deformation on the tension-testing machine. The maximum applied stress σ_{m1} was recorded. Then the sample was unloaded to $\sigma = 0$, where it had residual plastic deformation e_{d1}. Then we prepared the plastically deformed sample by triple loading-unloading in the elastic region of deformation from zero to σ less than σ_{m1} by 15–20 MPa; as a result, the mechanical and magnetic properties of the material of the sample acquired steady-state values. Then the coercive force was measured in the same region of the elastic deformation. After completion of the measurement cycle, the sample was plastically deformed to higher values $e_{m2} > e_{m1}$, and the measurement cycle was repeated. As a result, the dependences of the coercive force on the residual plastic deformation $N_c(e_d)$ (Fig. 3) and on the elastic deformation $N_c(e_{el})$ were obtained for the sample plastically deformed to the indicated values e_d (Fig. 4). From Fig. 3 it can be seen that the coercive force of the sample increases with the degree of plastic deformation, which is mainly caused by the increased density of defects of the crystal structure and gradients of internal stresses in the steel. Curve *1* in Fig. 4 shows the dependence of the coercive force on the elastic tensile deformation $N_c(e_{el})$ of the annealed sample. It can be seen that the dependence $N_c(e_{el})$ has the form characteristic for ferromagnetic steels: with increasing e_{el}, the coercive force first slightly decreases and then increases.

The nonmonotonic character of the dependence of the coercive force $N_c(e_{el})$ for steels in the region of elastic tensile deformation was repeatedly discussed in the literature (for example, see [3–6]). A slight decrease in coercive forces with increasing elastic deformation is explained by the formation of the magnetic texture along the direction of sample extension caused by the magnetoelastic effect for carbon steels whose magnetostriction is positive. With further elastic deformation, some authors explain the growth of N_c for steels by the change of the magnetostriction sign under the influence of elastic deformation; as a result, the type of the magnetic texture is changed [7]. Other authors (for example, see [3, 5]) consider that along with this, the growth of N_c is caused by gradients of internal stresses increasing with elastic deformation. The dependence $N_c(e_{el})$ for the annealed sample is reversible, that is, after removal of loading, N_c of the sample returns to its initial state without changing the shape of the curve. The dependences $N_c(e_{el})$ for the plastically deformed sample in general have the same character, as for the annealed sample, but are more pronounced (see curves *1–3* in Fig. 4). Thus, whereas the maximum change of the coercive force ΔH_c in the region of elastic tensile deformation for the annealed sample is ≈0.1 A/cm, for the sample with the residual plastic deformation $e_d = 1.9 \cdot 10^{-2}$, $\Delta H_c = 1.6$ A/cm (curves *1* and *2* in Fig. 4).

This phenomenon can be explained as follows. It is well known [8] that the iron lattice has the highly anisotropic Young modulus ($E_{111} \approx 2E_{100}$). As a result, as demonstrated in [5], internal stresses arise in polycrystalline steels after plastic tensile deformation and removal of loading. They induce magnetic anisotropy of easy plane type in

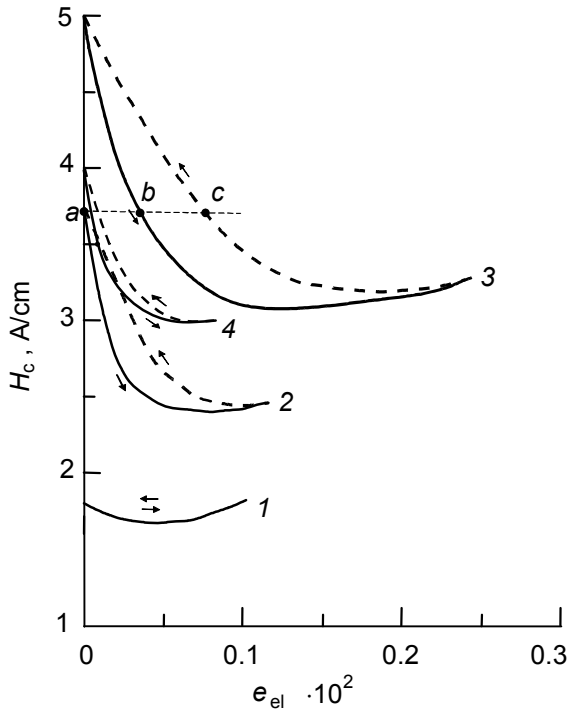

Fig. 4. Dependence of the coercive force on the elastic tensile deformation for the sample preliminary subjected to plastic deformation $e_d \cdot 10^2 = 0$ (curve *1*; the sample in the virgin state), 1.9 (curve *2*), and 11.1 (curve *3*); and after annealing of the sample in state *3* at a temperature of 300°C. Solid curves are for samples during loading, and dashed curves are after removal of loading from the sample.

the direction perpendicular to that of tension. Since N_c is measured along the direction of tension, magnetization reversal of the sample occurs in the hard magnetic direction, which leads to an increase in the coercive force. The elastic tensile stresses applied to such sample gradually convert the magnetic anisotropy induced by plastic deformation into anisotropy of easy axis type in the tension direction, which leads to a considerable decrease in N_c of the steel (curves *2* and *3* in Fig. 4). With further increase in the elastic tensile stress, a certain growth of N_c caused by the gradients of the internal stresses increasing with the elastic deformations is observed. If the steel is plastically deformed, the dependences $N_c(e_{el})$ have a hysteresis when these dependences measured during loading and subsequent unloading of the sample do not coincide forming a loop. As can be seen from Fig. 4, curves $N_c(e_{el})$ under tension of the sample lie below those registered after removal of tensile loading (dashed curves *2* and *3*). In addition, the magnitude of the hysteresis in these dependences is influenced by the degree of plastic deformation of the samples. In [1] it was suggested that the hysteresis of the coercive force during cyclic tension of the sample in the region of elastic deformation is caused by the occurrence of *free* carbon atoms unbound in carbide phases in plastically deformed steels.

It is well known that if carbon steel is well annealed, carbon atoms are mostly in the bound states in carbide phases. In this case, a small amount of impurity carbon atoms and atoms of other alloying elements are in the deepest potential wells. Upon elastic deformations of dislocations, the impurity atoms are reversibly displaced from the equilibrium position. As a result, the dependences $N_c(e_{el})$ during elastic cyclic tension of annealed steels are reversible and have no hysteresis (curve *1* in Fig. 4).

The plastic deformation of carbon steels results not only in the increase of the dislocation density and other defects of the crystal structure, but also in partial cementite decomposition. As a result, a considerable amount of free carbon atoms unbound in carbide phases and playing the role of impurity atoms arise [9, 10]. Free carbon atoms are

easily movable and can cause a hysteresis of the magnetic characteristics during elastic cyclic tensile deformation of the samples. For example, the impurity carbon atoms in the α-iron lattice can occupy positions in the centers of sides or edges of the cube. Each impurity atom creates tetragonal distortions of the lattice, causing tension along the axis of its location, and compression along the other axes. Without external applied stresses, all possible positions of interstitial atoms are equiprobable, and impurity atoms are statistically distributed along three cubic axes so that the lattice, on average, remains cubic. If a tensile stress is applied along one of the axes, the lattice will experience total tetragonal distortion in this direction. In this case, the positions of interstitial atoms along three axes cease to be equiprobable: it becomes more *favorable* for the free carbon atoms to be arranged on the expanded edges of the lattice. Gradually displacing to these positions, the carbon atoms cause additional tension, thereby increasing the degree of tetragonality of the lattice in this direction. As a result, the cubic α-iron lattice becomes more tetragonal, that is, more anisotropic due to the displacement of the impurity atoms during elastic tensile deformation.

The induced lattice anisotropy in the direction of tension increases the effective magnetic anisotropy constant and hence the coercive force of the material in this direction. After removal of loading, the impurity atoms are gradually expelled from the lattice, but with a delay in the deformation. As a result, the anisotropic lattice becomes cubic again, the effective magnetic anisotropy constant and the coercive force restore their former values, and the hysteresis loop of $N_c(e_{el})$ is closed after complete removal of loading. Thus, there are grounds to believe that the hysteresis coercive forces during elastic cyclic tension of plastically deformed samples are determined by the hysteresis of displacement of the impurity atoms (first of all, carbon) to the expanded regions of the crystal lattice during tension and their expelling from the lattice when the loading is removed. The delay of expelling of the impurity atoms from the α-iron lattice leads to higher values of N_c of the magnetic hysteresis loop after removal of loading compared to those during loading (curves *2* and *3* in Fig. 4). This hypothesis also explains the growth of the hysteresis of the coercive force with increasing degree of plastic deformation of the samples. Indeed, the plastic deformation increases the number of the free carbon atoms unbound in phases that, displacing during elastic tension in the iron crystal lattice, make the increasing volume of the sample anisotropic. This naturally leads to an increase in the hysteresis dependences $N_c(e_{el})$.

As an indirect proof of the existence of such mechanism of forming hysteresis of dependences $N_c(e_{el})$, low-temperaure annealing of steels can serve. The low-temperature (≈300°C) annealing of plastically deformed carbon steels reduces first of all the density of point defects, including free carbon atoms that, according to our representations, should lead to a decrease in the hysteresis of the coercive force. At the same time, the low-temperature annealing, removing internal stresses, changes only slightly the dislocation density in steels; therefore, the total level of N_c of such samples should remain sufficiently high, which is confirmed experimentally (curve *4* in Fig. 4). It is expected that long-term holding of plastically deformed samples at room temperature will also lead to a decrease in the hysteresis of these dependences. However, additional investigations are necessary here.

The results shown in Figs. 3 and 4 demonstrate that if the steel article preliminary experiences plastic tensile deformation and then is exposed to elastic cyclic tension, the identification of the stress-strain state of such article by measuring the coercive force becomes difficult. Indeed, if the magnetic prehistory of the steel is unknown, but its coercive force equal, for example, N_c = 3.7 A/cm, has been measured, according to Figs. 3 and 4, the following variants of its structural state can be realized: 1) the steel has been plastically deformed by tension to e_d = 0.019 (point *a* in Figs. 3 and 4), 2) the steel has been plastically deformed by tension to e_d = 0.116. After removal of loading, the sample is elastically deformed by tension to e_{el} = 0.00035 (point *b* in Fig. 4); 3) the steel has been plastically deformed by tension to e_d = 0.116, then loading is partially removed in such a manner that the sample remains under the effect of elastic deformation by e_{el} = 0.0009 (point *c* in Fig. 4). The above-indicated peculiarities of the influence of elastic and plastic deformations and of their combinations on the coercive force must be taken into account in the development of methods for investigation of the magnetic structure of stress-strain states of carbon steel articles.

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