MAGNETIC METHODS FOR TESTING ELASTIC-PLASTIC DEFORMATION OF POWDER STRUCTURAL STEELS

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The wide use of products manufactured from structural steels made by powder metallurgy is first of all dictated by lower power and material consumption. The safe work of powder steel machine parts and structural members under operating loads requires reliable methods for nondestructive testing of the stress-strain state. To inspect the quality of products made of carbon powder steels, magnetic structuroscopy is extensively used [1], as this technique is noted for express information gaining and convenient measurement taking. There are practically no works on determining the stress-strain state of powder steels, although this subject-matter has long been discussed for conventional steels [2].

Porosity affects both the mechanical and magnetic properties of sintered steels, therefore it requires special attention. This paper presents investigations into the effect of elastic-plastic strains on the magnetic characteristics of powder structural steels with different residual porosity, including those in different structural states. Structural states were modelled by rolling deformation.

Experimental procedure and materials

Specimens made of 50N2M-type steels (0.35 % C; 2 % Ni, 1 % Mo) with different porosity (4, 12 and 18 %) and Fe-C-type steels with different carbon content (0.03; 0.45 and 0.95 weight %) and initial porosity (8, 12 and 18 %) were studied. Steel St3 was used as a modelling material with zero porosity.

Composite powders (iron, graphite, nickel and molybdenum) were sintered in a continuous furnace at 1200°C within 2 hours in a dissociated ammonia atmosphere. The porosity of the specimens was varied by selecting the pressure of compacting. The specimens made of the powder steel 50N2M were tensile-type, 30 mm long in the gauge part and 5×5 mm^2 in the cross section The Fe-C specimens were 65×10×10 mm parallelepipeds with rounded faces.

The deformational behaviour of the magnetic characteristics of the steels were studied by specimen tension with simultaneous measurements of magnetic characteristics in a closed magnetic permeameter-type circuit in fields lower than 60 kA/m. Magnetization and magnetization reversal were effected along the specimen. Before tensile testing, to model different structural states, Fe-C-type steels were subjected to cold rolling with different amount of strain up to $\varepsilon_{\rm rol} \approx 30$ % ($\varepsilon_{\rm rol} = \frac{a_1 - a_2}{a_1} \cdot 100\%$, where a_1 and a_2 are specimen heights before and after rolling, respectively). The rolling was effected along the specimen at a constant rolling speed. After rolling, the specimens were ground and milled to give them a tensile-type form.

Results

Figure 1 shows the variation of the relative coercive force H_c/H_{c0} (the ratio between H_c at $\varepsilon \neq 0$ to its value before tension) measured on the major magnetic hysteresis loop for the iron-carbon specimens as they were tensioned.

In the elastic strain region the relative coercive force first decreases and then grows with deformation. The behaviour of the dependences $H_c/H_{c0}(\varepsilon)$ shown in Fig. 1 is much similar to that of the dependences measured on cast steels [5–9]. According to the information found in the literature, the nonmonotonic behaviour of the dependence in the elastic strain region is mainly determined by the effect of two factors, namely, 1) the magnetic texture produced during elastic deformation and associated with the domain structure rearrangement and 2) internal stresses, which grow monotonically with tension, particularly, in the plastic strain region. As a result of a competition between these two contrary trends, in the initial stage of deformation it is the magnetic texture that prevails first, and then, at greater amounts of strain, internal stresses dominate, with a minimum on the dependences $H_c/H_{c0}(\varepsilon)$. When external stresses exceed the yield stress, it is a rise in the density of crystal structure defects, first of all, dislocations, that becomes the main factor governing the variation of H_c.

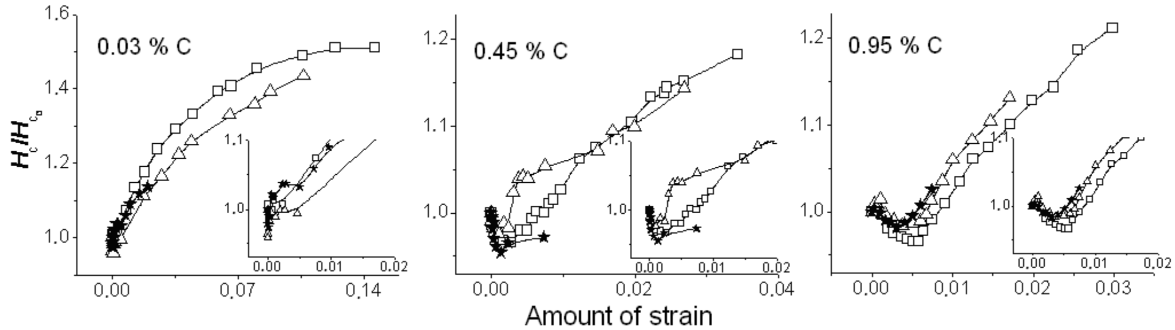

Fig. 1. The relative coercive force measured as the Fe-C specimens were tensioned.
(□ – P = 8 %, △ – P = 12 %, ★ – P = 18%).

Higher carbon content in Fe-C-type steels leads to a shift of the minimum on the dependences $H_c/H_{c0}(\varepsilon)$ towards higher strains due to a wider region of elastic tension. The effect of porosity on the behaviour of the dependences is only slight.

It was demonstrated in [3] that the rolling of Fe-C powder materials is accompanied by increasing internal stresses and material densification. The coercive force (H_c) of the Fe-C specimens grows monotonically with the amount of strain(ε_{rol}), and, obviously, this is due to increasing density of crystal structure defects, first of all, dislocations ($H_c \sim N^{1/2}$, where N is the density of dislocations [4]). When the behaviours of the coercive force is compared with the growth of the amount of strain for the Fe-C specimens and those made of steel St3, a similarity becomes apparent. However, referring to [3], as the amount of rolling strain grows, there appears anisotropy of the structural components in the direction of rolling.

In Fig. 2 the relative values of H_c/H_{c0} for the specimens studied are represented as functions of relative stresses $\sigma/\sigma_{0.2}$. This graph representation is convenient in that the value $\sigma/\sigma_{0.2}$ = 1 determines the boundary between the elastic and plastic regions of strain. The value $\sigma/\sigma_{0.2}$ = 1 is marked in Fig. 2 by a vertical line. Similar curves for steel St3 are given for comparison.

Consider the deformation behaviour of the coercive force of specimens made of nonporous steel St3. The coercive force of the initial (undeformed) specimen is seen (Fig. 2g) to vary with deformation by the law characteristic of isotropic steels saying that in the elastic region there is a minimum of the coercive force, whereas in the region of plastic strains a monotonic growth of the coercive force is observed. Plastic deformation by rolling entails a clear minimum of the coercive force, approximately the same for all amounts of rolling strain. A similar effect was observed in [11] for specimens made of steel St3, which were previously plastically deformed by tension. It can be supposed that plastic deformation by rolling brings about such a stress texture that the magnetoelastic effect occurring in specimens under tension becomes more pronounced. In the region of plastic tensile strains higher values of the coercive force are observed for specimens subjected to heavier rolling deformations, and this corresponds to general knowledge.

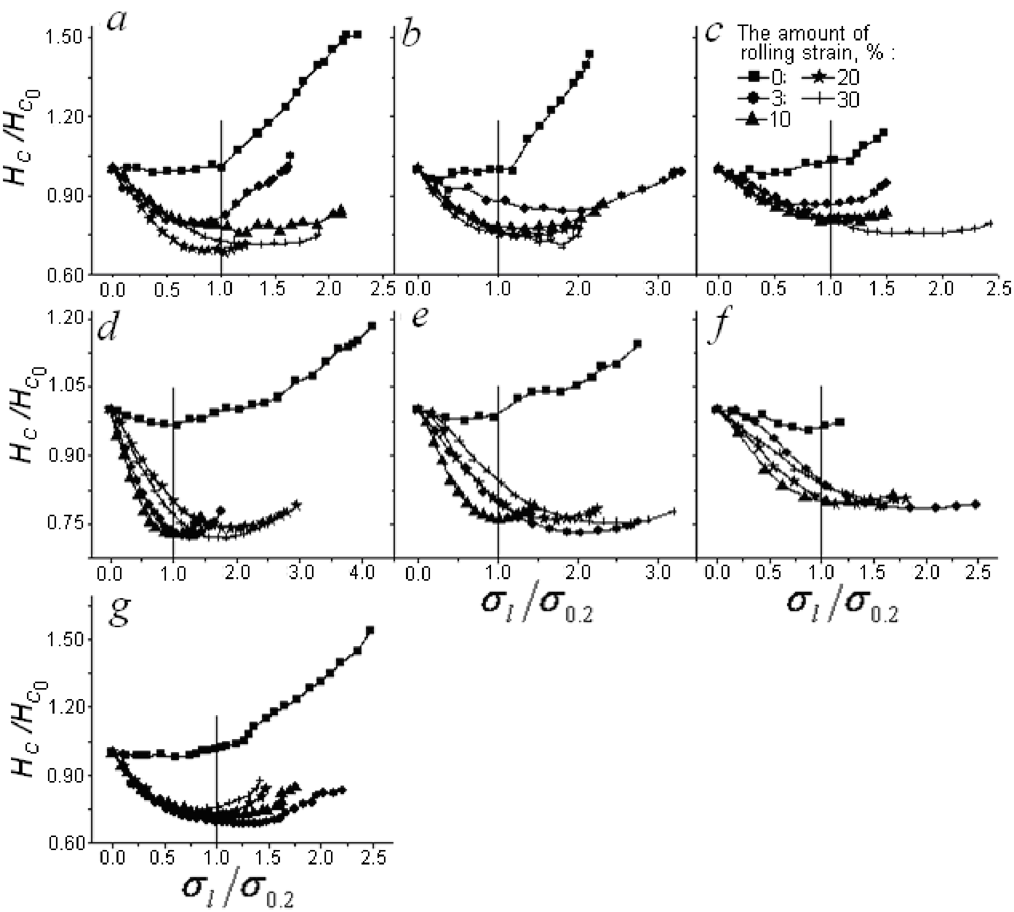

Fig. 2. Relative coercive force as a function of tensile stresses referred to yield stress for Fe-C specimens with a carbon content of 0.03 weight % (*a*, *b*, *c*) and 0.45 weight % (*d*, *e*, *f*) and steel St3 specimens (*g*). Initial porosity: 8 % (*a, d*); 12 % (*b*, *e*); 18 % (*c*,*f*).

The behaviour of the coercive force as a function applied tensile stresses on powder steel specimens is roughly similar to that observed for St3 specimens (Fig. 2). As for St3 specimens, the curves representing the coercive force as a function of stresses in powder specimens deformed by rolling have a pronounced minimum. However, it does not seem possible to discuss the effect of porosity on these curves for two reasons. Firstly, the porosity of the rolled specimens decreases, and sometimes considerably ([3], see the table), the shape of the pores changes. Secondly, the rolling deformation of porous specimens is a complex process, much different from the deformation of cast ones [10], and, probably, this tells on the magnetic properties of the former.

In a number of studies [8, 9, 11] conducted on conventional cast steels under tensile deformation it was demonstrated that the position of the minimum H_c is reached at the instant of a partial compensation of internal material stresses by external applied stresses of the opposite sign. Consequently, the value of external tensile stresses at which there is minimum H_c can offer an estimate to internal (compressive) stresses in steels. It is obvious from Fig. 2 that there is no regular relation between the minimum of the coercive force and the value of rolling strain (and, consequently, internal stresses) of the specimens studied, including those made of conventional cast steel St3. In [3] the internal stresses of rolled specimens were shown to be proportional to rolling strain ε_{rol}. Internal stresses were determined by the X-ray technique, and this technique is known to offer information on stresses in the thin surface layer (20 μm and thinner). It is pertinent to suppose that the compressive stresses in the subsurface layer are compensated mainly by the tensile stresses localized inside the specimen. Since after rolling the specimens were given a tensile-type form with material removal from the surface, the pattern of the stress state may have become slightly distorted. Hence it follows that rolling deformation produces such orientation of internal stresses that they fail to be determined by the magnetic method outlined in [8, 9, 11]. Conceivably that is why the minimum of the coercive force on the dependences $H_c(\sigma)$ is sometimes found deep in the plastic strain region (e. g., Fig. 2*d*, *e*).

By way of summary it can be said that, when porous specimens are rolled, the stress texture formed in them is approximately the same as in nonporous St3 specimens, and this is what governs the general behaviour of the coercive force as a function of tensile strain.

Figure 3 shows the variation of the relative coercive force of specimens made of sintered steel 50N2M as they are tensioned. The behaviour of the dependence $H_c/H_{c0}(\varepsilon)$ also repeats the behaviour of the coercive force for the materials discussed above. In the elastic strain region the relative coercive force first decreases and then, as the deformation grows, increases. However, for the alloyed steel studied, the following peculiarity is obvious. When the external stresses exceed the yield stress, with porosity rising from 4 % to 18 %, despite almost indentical increase in the dislocation density during plastic deformation, the coercive force of the specimens grows insignificantly. At the same time, on the dependences $H_c(\varepsilon)$ there is a greater dip in the coercive force ΔH_c for higher porosity. Simultaneously, the minima of H_c are "smeared" along the axis of deformation (Fig. 3*a*).

In conventional cast steels there always is some volume of closure domains caused by a necessity of reducing the magnetostatic energy of differently oriented grains of polycrystals and submagnetic cementite inclusions. In materials with a cubic lattice the closure domain structures are, as a rule, formed by 90° neighbourhoods [13]. In powder steels, in addition, a region of a distorted closure domain structure is formed near the pores; it can be assumed that, as porosity increases, the volume of these closure domain regions also increases. Hence it follows that in powder steels the volume of 90° neighbourhoods is much bigger than in cast steels, all other factors being the same. The volume of 90° neighbourhoods increases with porosity. Since the formation of induced magnetic texture in elastic tension is accompanied by a reduction of the volumes of 90° neighbourhoods, this reduction is more active in a material with higher porosity (Fig. 3).

In Fig. 3 *b*, *c* the dependences $h_c^{0.4}/h_{c_0}^{0.4}(\varepsilon)$ and $h_c^{0.05}/h_{c_0}^{0.05}(\varepsilon)$ are presented for specimens with different porosity after magnetization in medium (maximum induction in magnetization B_{max} = 0.4 T) and low (B_{max} = 0.05 T) fields. These curves are seen to be practically independent of porosity, and the minimum values of h_c/h_{c_0} on the ε-dependence for specimens with different porosity have closely spaced values. When the values of microstresses [14] determined by the minima of the strain dependences of the coercive force [9] on the major and minor hysteresis loops as related to their values at zero strain are compared with those obtained by the X-ray analysis, the following becomes evident. As porosity grows, the values of internal stresses decrease. The values determined by X-ray diffraction analysis are the closest to those obtained by the dependence $h_c^{0.05}(\varepsilon)$. That is, when the maximum magnetic induction decreases, the obtained values of microstresses agree better with those determined by X-ray diffraction analysis. The reason is that domain walls "catch" on pores at lower fields and, affected by a low applied magnetic field, cannot come off from them. Thus, the effect of pores on the coercive force is smoothed, and the measured values of magnetic characteristics better conform to the true stress state of the material.

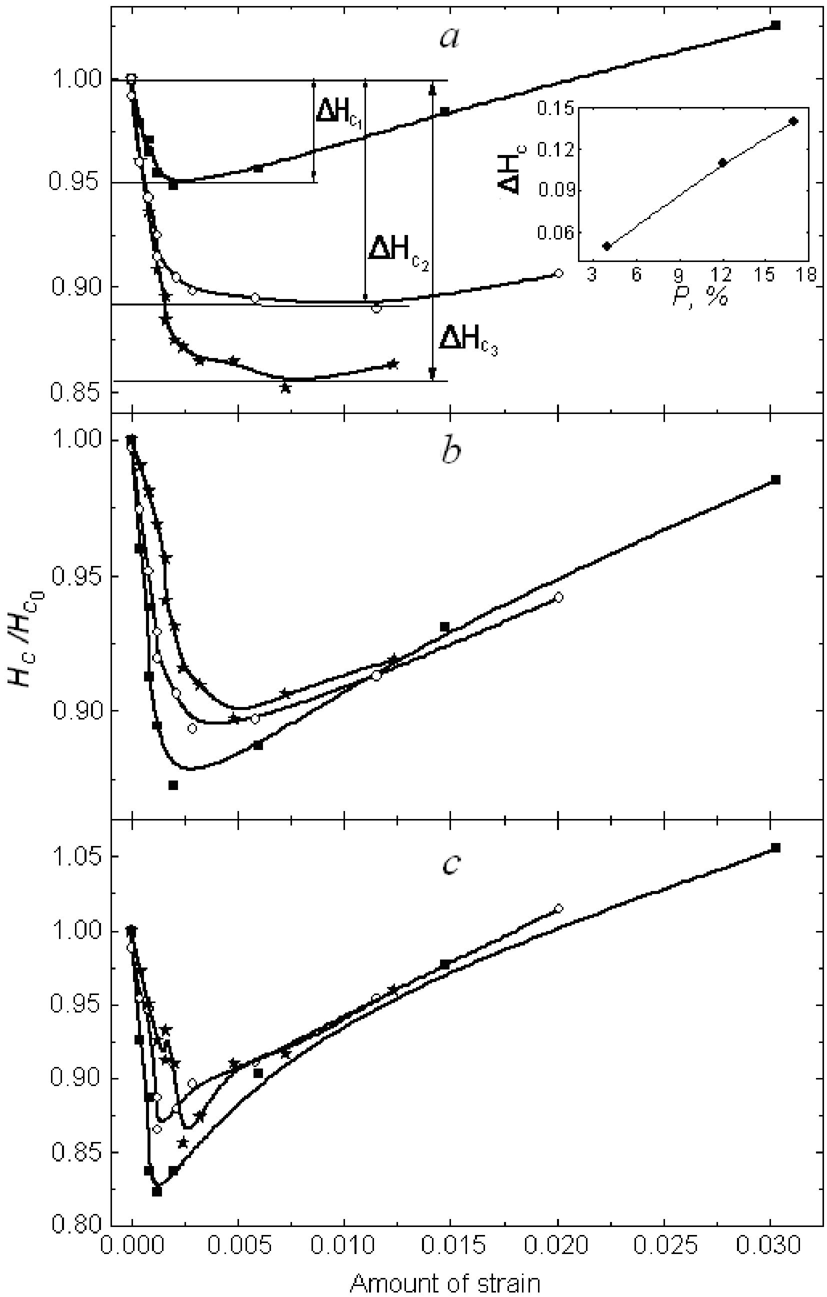

Fig. 3. Relative coercive force as a function of tension for specimens made of sintered steel 50N2M (■ – $P = 4$ %, ○ – $P = 12$ %, ★ – $P = 17$%).
a — major hysteresis loops; *b* — minor hysteresis loops at $B_{max} = 0.4$ T;
c — minor hysteresis loops at $B_{max} = 0.05$ T.

Conclusion

The tensile strain dependences of the coercive force for sintered steels of the Fe-C and 50N2M types have been shown to have a similar behaviour. In the initial region of deformation the coercive force first decreases, and then increases at the onset of developed plastic deformation, with the minimum being formed in the region of partial compensation of internal stresses by external stresses.

It has been shown by the example of the powder steel 50N2M that higher porosity is accompanied by a greater fall in the coercive force ΔH_c. This is because the volume of 90° neighbourhoods grows with porosity. Since the appearance of induced magnetic texture under elastic tension is accompanied by reduced volume of 90° neighbourhoods, this reduction is more active in a material with higher porosity.

A possibility of selecting such a magnetizing field that the coercive force of a minor magnetic hysteresis cycle for 50N2M steel specimens is less dependent on porosity has been demonstrated. It has been suggested that the applied stress at which the minimum coercive force of this minor cycle occurs, corresponds to the internal stresses of a porous material.

Rolling distorts the form of the dependences $H_c(\sigma)$ characteristic of conventional carbon steels, with a bend near point $\sigma_{0.2}$ in tensile deformation, which enable the yield stress of a material to be determined by magnetic measurements. Therefore the determination of the yield stress region remains feasible only on unrolled isotropic powder steel specimens.

The monotonic behaviour of the coercive force in elastic uniaxial tension suggests that the stress-strain state in structural members made of sintered steels can be estimated under operating loads.

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