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CHANGES OF COERCIVE FORCE OF STEEL SAMPLES WITH VARIOUS DUCTILITY REACHED BY THERMOMECHANICAL PROCESSING AT STRETCHING

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Abstract. The article deals with peculiarities of the changes of the coercive force at uniaxial static tension of structural steel samples depending on the material state (initial or preliminary strengthened).

Steel strengthening is carried out by equal-channel angular pressing. Flat steel samples were stretched with an "Instron-1195" testing machine at room temperature. The coercive force was measured by a fluxgate coercimeter at step loading conditions.

The analysis was made of combined charts of strain «s-e» and coercive force H_c dependence on coercive force "H_c-ε" of the steel sample strain. Changes of H_c are explained. The domain structure in steel was analyzed. The influence of the material state on the character of correlation between "σ-ε" and "H_c-ε" is shown.

1. INTRODUCTION

To objectively evaluate the reliability of metal construction elements defined by the safety factor of structures, it is necessary to know structural and deflected mode states of the structural element. The determination of the dependence of the magnetic characteristics on strain and stresses opens up possibilities for the evaluation of the mode of deformation state of ferromagnetic materials. To estimate the real state of the material and the residual life of the structural element, magnetic diagnostics is actively used. The coercive force is often taken as the main magnetic parameter, as it is most sensitive to the changes of dislocation density and since it often obeys a linear relationship with the mechanical properties. The detailed analysis of the differences of the quantities of the coercive force and other magnetic properties of ferromagnetic steels in loaded and unloaded states at their plastic stretching is made in [1].

Interrelation between stresses and strain, on the one hand, and magnetic properties, including coercive force, on the other hand, for different steels (St3 steel in the annealed state and steel 45 in air-hard-

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Table 1. The mechanical properties of St3sp steel in different states.

No	*State of Material*	*Yield strength, MPa*	*Ultimate tensile strength, MPa*	*Ductility, %*
1	Initial state – as-received condition + short-time annealing at 673K	313.8	494.4	15.2
2	1) Water quenching from 1133K; 2) ECAP, «B_c», 673K, *n*=8; 3) Short-time annealing at 673K.	359.7	709.4	2.4

ened state as well as subjected to quenching and tempering) is given in [2]. In [3] the studies of the location shift of the coercive force minima at elastic stretching of St3 and U8 steels with changing of the residual compressive stresses of the first order are presented.

In the course of the operating process the structural material element is known to degrade, damage, change its plasticity, strength, and other properties. In this connection, it is interesting to investigate the materials which, being subjected to preliminary loading, acquired certain defects and residual strain.

The article discusses peculiarities of changes of the coercive force at uniaxial static stretching of St3sp construction steel samples depending on the material state (after annealing of initial material and thermomechanical processing).

2. MATERIAL AND TEST PATTERN

The investigated material: St3sp structural low-carbon steel in the annealed state and after thermomechanical processing (TMP) by "quenching + ECAP + annealing" pattern. The chemical composition of the investigated steel: 0.17% C, 0.2% Si, 0.54% Mn, 0.14% Cr, 0.14% Ni, 0.25% Cu, and the rest — Fe.

The coercive force of samples at their stretching was measured for St3sp steel in two states: 1) after short-time annealing at the temperature of 673K and 2) after TMP by "water quenching at 1133K + ECAP by route "B_c" in *n*=8 passages at 673K + short-time annealing at 673K" pattern. The channels intersection angle of ECAP accessory ϕ=120° (Fig. 1). Sample strain degree at ECAP after 8 passages ε_8=5.34.

Obtained blanks were used to produce the flat samples of I type with 50×5×2.5·10^{-2} m working surface to be tested for static rupture. The stretching tests were made at room temperature at "Instron-1195" testing machine at constant loading speed of ≈1.67·10^{-5} μs^{-1}.

3. RESULTS AND DISCUSSION

The mechanical properties of St3sp steel are given in Table 1. In comparison with annealed St3sp steel the material subjected to quenching, ECAP, and annealing has ~1.14÷1.43 times higher strength and 5.3 times lower ductility.

The coercive force was measured with the help of a fluxgate "KIMF-1" coercimeter at step loading of a sample, i.e. at the certain strain level sample loading was suspended without unloading; then the sensor was applied to the surface and oriented along the sample, magnetic field being directed along the sample stretching axis. Rendering the coercimeter milliamperemeter readings were rendered by gauge dependence taking 0.1 A·m^{-1} control sample as a reference.

H_c is known to be determined by vector sum of acting stresses of the first, second, and third orders. Third-order stresses are defined by the metal's fine structure and depend on composition, lattice type, presence of inclusions, and dislocation density. Second-order stresses are formed at the structures' assembly, thermal processing and loading of structural elements. They increase the coercive force and form residual stress fields in the metal. The external load create first-order stresses in a structural element that, imposed on the previous, change H_c value in elastic strain field. At the transition to plasto-elastic zone, external stresses dominate increasing H_c.

Fig. 2 shows dependence of coercive force H_c on strain at the stage of uniform stretching St3sp steel sample No. 1. It should be noted that strength properties and coercive force are known to have similar dependencies on dislocation densities. Decrease

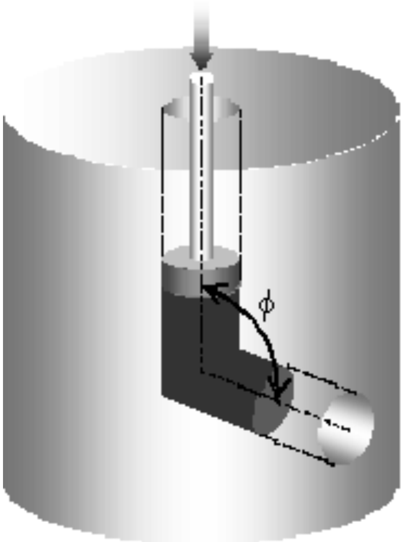

Fig. 1. ECAP scheme.

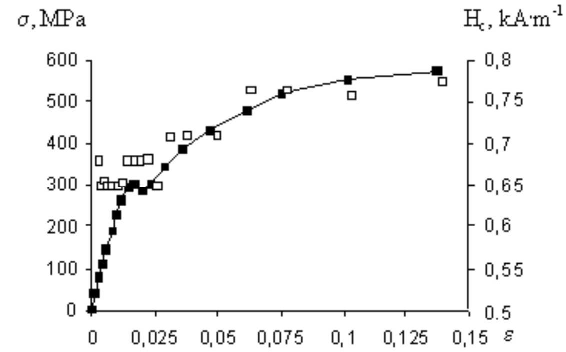

Fig. 2. Strain chart and dependence of coercive force on strain for St3sp steel subjected to short-time annealing below the critical range.

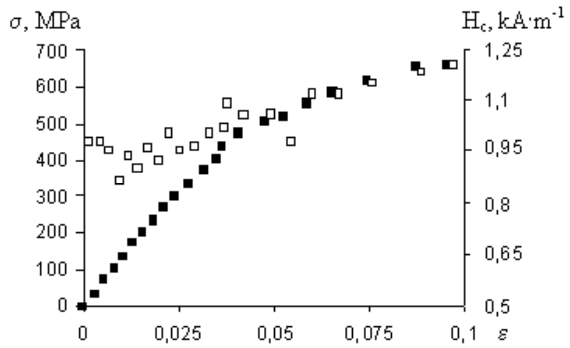

Fig. 3. Strain chart and dependence of coercive force on strain for St3sp steel subjected to quenching, ECAP, and short-time annealing below the critical range.

of H_c value at the initial stage of elastic deformation of the material is described in [2,4] and is defined by the positive magnetoelastic effect. Having reached the yield point, H_c increase discontinues. The H_c increase at strain is caused by dislocation density growth. Earlier we used the method to study changes of coercive force of 10kp5 steel samples with various ductility at stretching [5].

The material strengthening according to the given regime is reflected in the strain chart (Fig. 3) featured by the absence of yield line, higher strength properties, and low ductility. Quenching, ECAP, and short-time annealing of St3sp steel (regime No.2) leads to substantial increase of coercive force (Fig. 3). Considerable increase of H_c for samples subjected to TMP is defined by a number of factors. TMP leads to significant increase of dislocation density, thus contributing to H_c growth.

The grain size and orientation change due to thermal processing in the form of quenching and annealing below the critical range, as well as intensive plastic strain influence magnetic domain configuration, domain boundary mobility, and structure-sensitive magnetic properties, including coercive force.

In the present work a magnetic-force microscopy technique was used to obtain MFM images. A scanning probe microscope "SmartSPM" ("AIST-NT" Co. Ltd., Moscow, Zelenograd) was used. As an example to illustrate influence of intensive plastic strain and thermal processing on microstructure and domain configuration, Fig. 4 shows MFM images of St3sp steel in an as-received condition (a) and after ECAP by route "C", temperature of 673K, and n=8 pressing passages (b).

The width and length of magnetic domains are known to depend on polycrystal grain size. Average size of St3sp steel grains in the initial state is 18-20 μm, of strengthened steel — 6-7 μm. In their turn, magnetic domain sizes vary over a wide range: in the initial state domains' length L≈4-36 μm, width d≈1-4.5 μm; in the strengthened state L≈1.5-24 mm, d≈0.5-2 μm. Thus, larger domain sizes correspond to larger grains. As noted in [6], the present experimental data on connection between grain sizes and domain sizes in polycrystals are rather controversial, what is probably caused by differences of tested samples by orientation and thickness. The problem is not considered here.

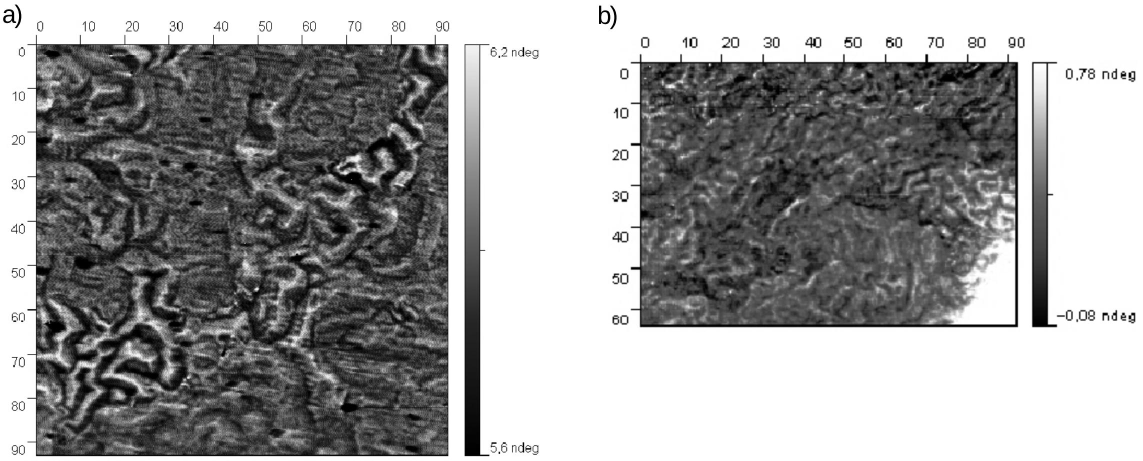

Fig. 4. MFM images of St3sp steel samples: a) initial state — as-received condition; b) after ECAP (route «C», *T*=673K, *n*=8) (scan size: 90×90 μm и 90×60 μm, respectively).

As seen from MFM images, the magnetic domains have bent forms. The bend of domain boundaries may be due to small irregularities, contingencies in the moment of domain configuration origination or effects of heat chaotization. Also, domain branching is observed. This can be attributed to the fact that, in our case, the plate thickness is rather high and, as shown theoretically by E.M. Lifshits, domain branching takes place at a sample surface.

The changes of magnetic properties of the ferromagnetic materials are defined by reorientation (mobility) of magnetic domains in the process of magnetization and remagnetization [6]. In steels, the coercive force is determined mainly by the force of interaction between moving domain boundaries with various crystal structure defects and magnetic imperfections (crystal defects, grain boundaries, pores, non-magnetic inclusions).

As the main factor impeding the domain wall movement is the grain boundary, at grain size reduction as a result of TMP, with the higher grain quantity in unit volume and higher proportion of grain boundaries, delay or deceleration of domain walls movement takes place, thus causing the coercive force increase. In this connection, H_c value is higher for the strengthened steel with smaller grains comparing to the coarse-crystalline steel. Besides, higher inner stresses and dislocation density also facilitate H_c growth.

4. CONCLUSION

Thus, for St3sp steel strengthened by thermomechanical processing in comparison with the initial state steel higher coercive force values are caused by influence of substantially high dislocation density and deceleration of domain walls movement.

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