The Use of Magnetic Methods for the Estimation of Plastic Deformation under Cyclic Loading of Annealed Medium-Carbon Steel

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Abstract. The influence of fatigue stressing of annealed medium-carbon steel (with 0.45 wt. % of carbon) on the change of magnetic characteristics of the steel, in particular, coercive force and residual magnetic induction for major and minor magnetic hysteresis loops has been investigated. It has been shown that the magnetic characteristics considered are sensitive to both large and small plastic deformations accumulated under fatigue loading. The dependences of residual mechanical properties on the number of cycles (accumulated plastic deformation) have been established, as well as correlation between coercive force for minor magnetic hysteresis loops in weak fields (Rayleigh region) and residual elongation. The possibility of magnetic nondestructive testing of accumulated plastic deformation and estimation of the residual material life of a material under cyclic loading has been demonstrated.

Introduction

Most machines and constructions have parts that work under cyclic loading conditions with different stress levels and different regularity of cycles. Respectively, depending on operation conditions, the stress level can vary over a wide range and exceed both fatigue limit and yield stress of a material, and thus strains are brought about in machine parts. This makes the study of fatigue resistance, the prediction of durability and residual material life more complicated. It is therefore necessary to apply the methods that, along with collecting experimental data, allow us to understand the physical background of fatigue as a phenomenon. In this connection, the application of nondestructive test methods is very promising. Among the magnetic characteristics, coercive force and residual magnetic induction are more often reported to be used for estimating physical and mechanical properties of a material under deformation [1, 2].
Under deformation, coercive force and residual magnetic induction are influenced by a change in dislocation density and appearance of discontinuities (plastic loosening, microcracks and voids) [1, 3]. The initial stage of deformation is accompanied by the formation of dislocation cell structure as early as at small strains. Dislocation density within the cells reaches saturation rapidly and has almost no further changes upon deformation. Only small decrease of cell dimensions is observed. Meanwhile, dislocation density on the cell walls continuously increases up to fracture, the formation of cracks and voids being possible on the structure areas [4]. In this connection, it seems reasonable to divide the change of magnetic characteristics and microstructure of the material under deformation

into three stages, namely, 1) at low strains; 2) at middle strains; 3) after large strains [3]. It is also necessary to note the common nature of plastic deformation accumulation under static and cyclic loading [5].
Thus, the aim of the present work is to investigate the influence of fatigue stressing of annealed medium-carbon steel (with 0.45 wt. % of carbon) on the change in the magnetic characteristics of the steel.

1. Experimental procedure and material

Industrial cast medium-carbon steel with 0.45 wt. % of carbon was investigated. The steel was subjected to annealing at 800°C for 8 hours and subsequent slow cooling with oven to room temperature. To determine initial mechanical properties, round button-headed tensile specimens 5 mm in gauge diameter and 25 mm in gauge length were machined. For cyclic loading, round button-headed specimens 5 mm in gauge diameter were used. Before mechanical testing the specimens were electrically polished in 90%CH_3COOH+10%$HClO_4$ electrolyte at voltage 25 V for 6 minutes.
Cyclic loading of the specimens were carried out with a controlled value of total deformation $\varepsilon_{tot}=2\varepsilon_a=\varepsilon_{el}+\varepsilon_{pl}=0.76\%$ (where ε_a is deformation amplitude, ε_{el} is the elastic part of deformation, ε_{pl} is the plastic part of deformation), pulsating deformation cycle, triangular change of deformation amplitude and loading frequency of 0.5 Hz. The testing was conducted so that the cycle asymmetry coefficients ($R_\varepsilon=\varepsilon_{min}/\varepsilon_{max}$, $R_s=S_{min}/S_{max}$) met the condition $R_s=R_\varepsilon=0$. The specimens were cyclically loaded with 5, 10, 50, 200, 400 cycles. After fatigue stressing with a given number of cycles and measuring the magnetic characteristics, the specimens were subjected to tensile testing in order to determine residual mechanical properties. Mechanical tests were conducted on the Instron 8801 servohydraulic testing machine.
Magnetic characteristics were measured for major and minor magnetic hysteresis loops. The following magnetic characteristics were obtained: coercive force and residual magnetic induction for the major magnetic hysteresis loop (H_{max}=60 kA/m) and minor ones corresponding to the maximal magnetic induction of a hysteresis loop b_{max} = 1; 0.4; 0.1; 0.05 T respectively. The magnetic measurements were conducted on round button-headed specimens before and after fatigue stressing with the use of the Remagraph magnetic measuring instrument.

2. Results and discussion

The annealed initial condition is characterized by minimal values of the coercive force, see the table.

Table. Coercive force and residual magnetic induction values for the steel under study in initial annealed condition (the number of cycles N=0, accumulated plastic deformation ε_Σ=0)

b_{max}=0.05 T		b_{max}=0.1 T		b_{max}=0.4 T		b_{max}=1 T		H=60 kA/m (major loop)	
h_C, A/m	b_r, T	h_C, A/m	b_r, T	h_C, A/m	b_r, T	h_C, A/m	b_r, T	H_C, A/m	B_r, T
15.55	0.017	31.8	0.043	99.7	0.3	146.2	0.766	194.5	1.159

Under cyclic loading, increasing structural imperfection density is accompanied by increasing values of the critical fields of interaction between domain boundaries and defects [6]. This results in the growth of coercive force values for both major and minor magnetic hysteresis loops (fig. 1*a*, *b*). Note a considerable difference between the variation of the coercive force in strong fields and that in weak ones. For weak fields (up to 0.1 T inclusive, when the maximal hysteresis loop field $h_{max}<H_c$), the coercive force for minor magnetic hysteresis loops continuously rises during the whole deformation process, and its sharp increase is observed at the early stage of deformation, which subsequently gives way to a smoother growth at larger deformations. The reason is that, in weak magnetic fields, domain boundaries interact mainly with single dislocations or structural imperfections having small critical fields $H_{critical}\approx h_{max}$, .

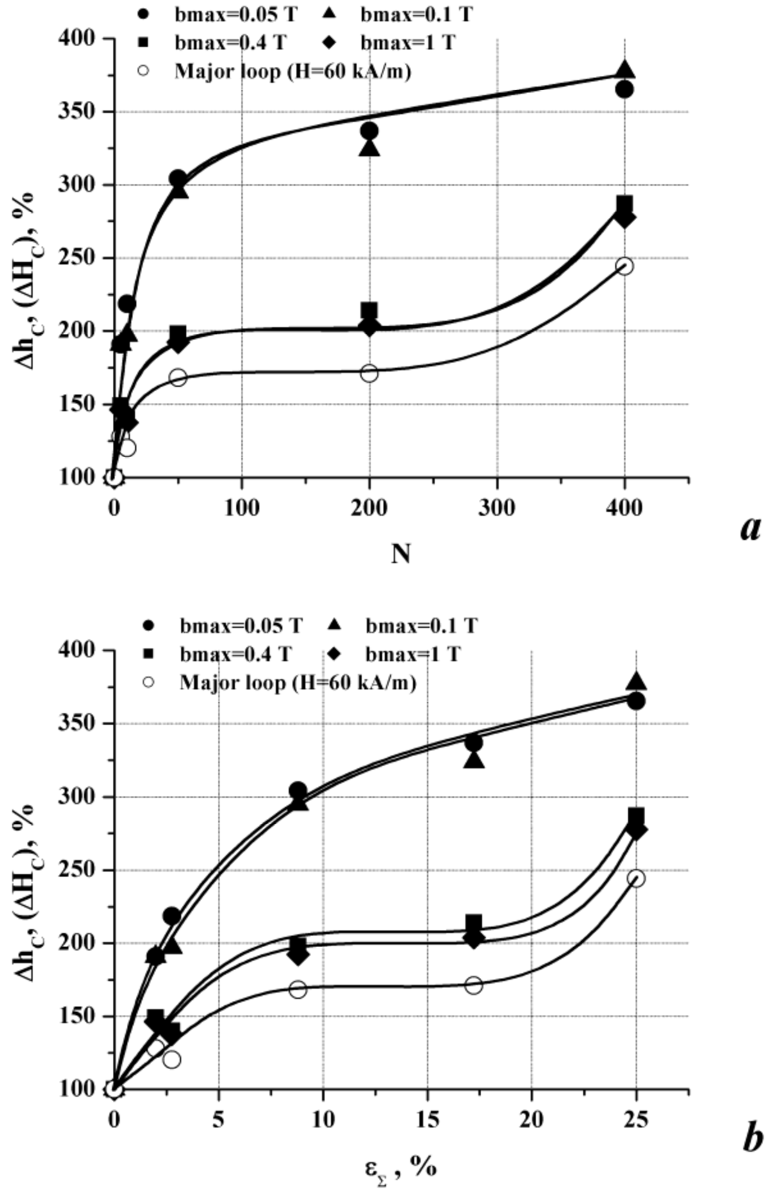


Fig. 1. Relative change of the coercive force as dependent on the number of cycles (a) and accumulated plastic deformation (b) for the steel under study. Coercive force values for the steel under annealed initial condition are taken to be 100% (see the table).

Under alternating magnetization in stronger fields, one can see the stabilization of coercive force values as the accumulated plastic deformation varies between 7-10% and 15-17%.

The stabilization can be caused by the formation of the dislocation cell structure. In this case the domain boundaries interact with both single dislocations and cell walls [6]. Further deformation is again accompanied by the growth of coercive force values, and this can be explained by the appearance of microscopic voids, which grow in size and number up to fracture. Being the source of leakage fields, the microscopic voids counteract alternating magnetization according to "the inclusion theory" [7].

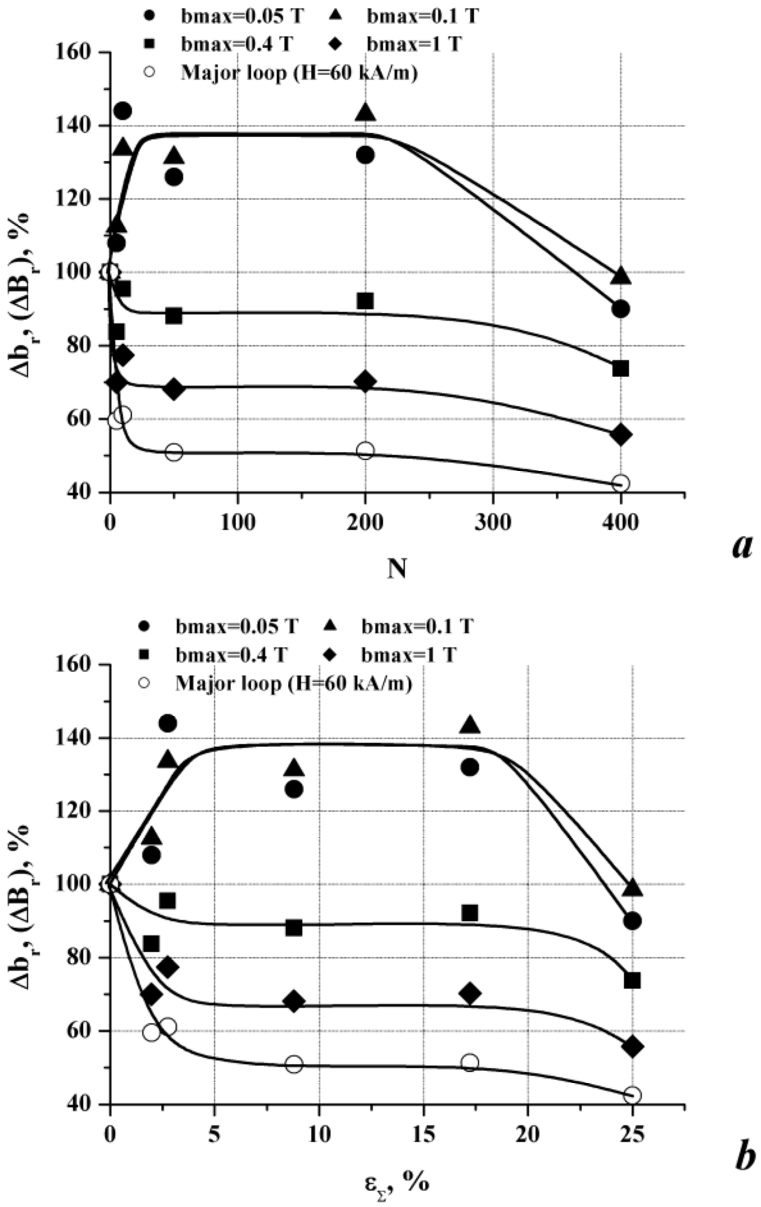


Fig. 2. Relative change of residual magnetic induction as dependent on the number of cycles (*a*) and accumulated plastic deformation (*b*) of the steel. The values of residual magnetic induction for the steel under annealed initial condition are taken to be 100% (see the table).

In the early stage of deformation, at accumulated plastic deformation up to 7-10%, the values of residual magnetic induction decrease for the major loop and the minor loops corresponding to the maximal magnetic induction b_{max}=1 and 0.4 T, whereas (at accumulated plastic deformation up to 2-3%) they increase for the minor loops corresponding to the maximal magnetic induction b_{max}=0.1 and 0.05 T (fig. 2*a*, *b*).

Thus, as is the case with the coercive force, there is a difference between the variation of residual magnetic induction in strong fields and that in weak ones. On the one hand, segments with large local microstresses (in particular, dislocations) are the spots where magnetic reversal centers are easily generated [7]. This contributes to a decrease in residual magnetic induction for strong fields. On the other hand, dislocation redistribution leads to the appearance of areas with a less imperfect structure. Magnetization in weak fields is accompanied by small domain boundary displacements, which no not seem to exceed the sizes of these areas. Therefore the values of residual magnetic induction for weak fields grow up to the complete formation of the dislocation cell structure in the whole bulk of the material. The values of residual magnetic induction stabilize thereafter up to 15-17% of accumulated plastic deformation. Further deformation is accompanied by decreasing residual magnetic induction regardless of the field magnitude, which is attributable to the appearance of microscopic voids. Macrodefects, in particular cracks and voids, are the spots where leakage fields arise [7]. These leakage fields have the opposite direction to the magnetization field, and this finally leads to decreasing residual magnetic induction.

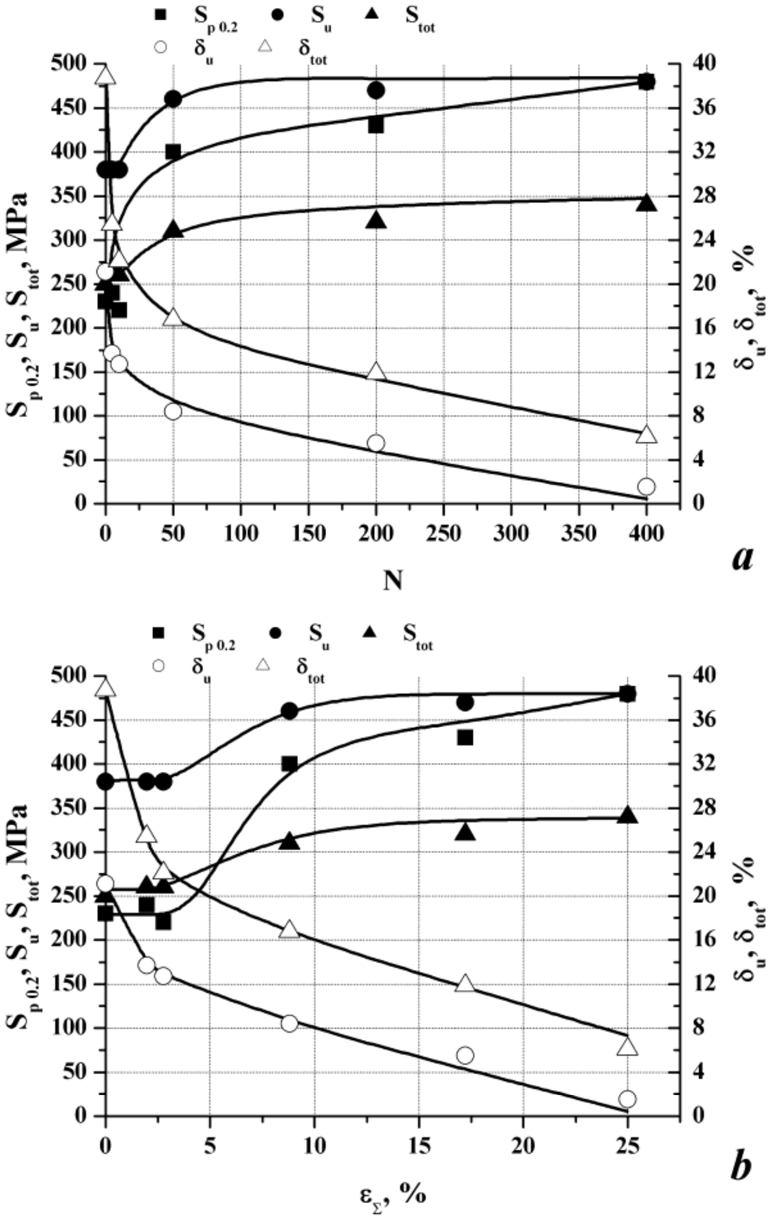
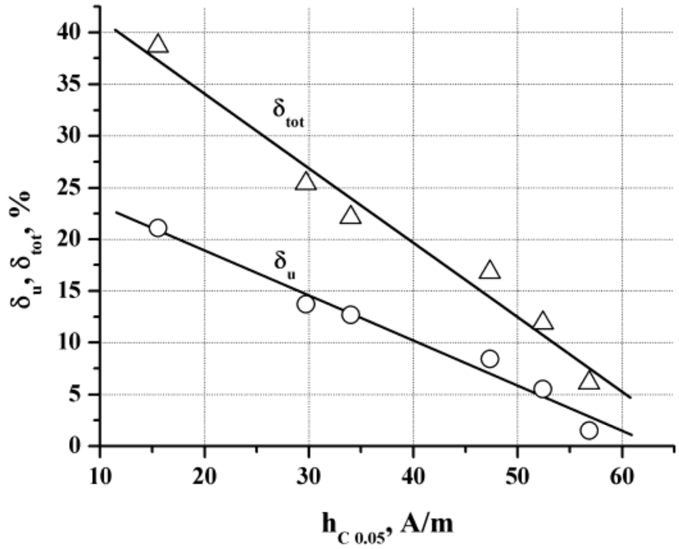
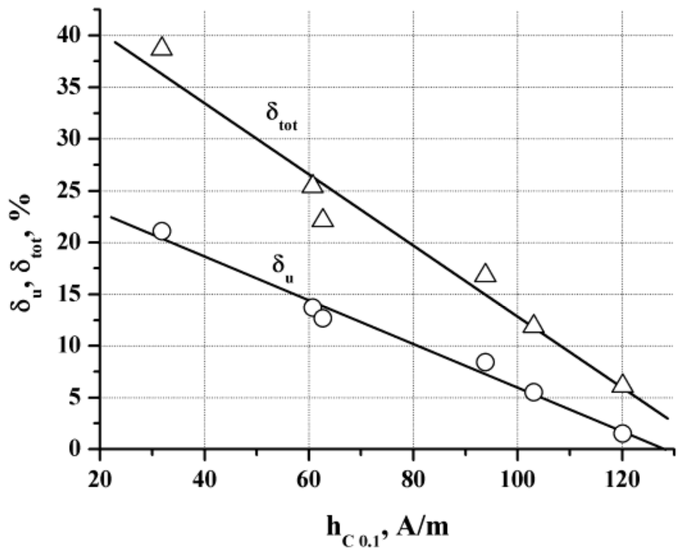


Fig. 3. The variation of residual mechanical properties under tensile testing depending on the number of cycles (*a)* and accumulated plastic deformation (*b*) of the steel under study.

Fig. 3 represents the variation of strength characteristics (0.2% proof strength $S_{p0.2}$, ultimate tensile strength S_u, fracture stress S_{tot}) and plasticity characteristics (uniform elongation δ_u, total elongation δ_{tot}) of the steel under fatigue stressing. It can be seen from fig. 3 that, even at the early stage of deformation, a sharp decrease in plasticity characteristics occurs, which is followed by a smoother decrease. In the early stage of deformation up to 2-3% of accumulated plastic strain, the strength characteristics retain their initial values, and then they continuously grow under fatigue stressing. Besides, the 0.2% proof stress shows a steeper increase than the ultimate tensile strength.



a



b

Fig. 4. Relationships between the variation of the plasticity characteristics and the magnetic characteristics of the steel under study.

Fig. 4 shows correlations allowing the plasticity characteristics of the steel to be determined as functions of the coercive force. Note that fatigue stressing has practically offered the so-called limiting condition of the material, when yield stress and ultimate tensile strength become the same and when elongation is zero. Thus, using the dependences obtained, one can estimate the residual life of a material subjected to low-cycle fatigue stressing. The experimental results have offered analytical equations relating magnetic characteristics ($h_{C\,0.05}$, $h_{C\,0.1}$) to those of plasticity (δ_u, δ_{tot}), namely,

$$\delta_u = 27.5927 - 0.43545 \cdot h_{C\,0.05}, \qquad R = -0.989;$$
$$\delta_{tot} = 48.43112 - 0.71935 \cdot h_{C\,0.05}, \qquad R = -0.986;$$
$$\delta_u = 27.01901 - 0.2102 \cdot h_{C\,0.1}, \qquad R = -0.993;$$
$$\delta_{tot} = 47.26525 - 0.34447 \cdot h_{C\,0.1}, \qquad R = -0.982,$$

where δ is measured in % and h_C in A/m, R being the correlation coefficient.

3. Conclusion

Dependences relating the variation of the coercive force and residual magnetic induction for major and minor magnetic hysteresis loops to the number of loading cycles (accumulated plastic deformation) under low-cycle fatigue stressing have been obtained, and they testify to the sensitivity of the magnetic characteristics considered to both large and small plastic deformations. The feasibility of magnetic nondestructive testing of plastic deformation accumulated under cyclic loading has been demonstrated.

A relationship between the behaviour of residual mechanical properties and the number of loading cycles (accumulated plastic deformation) has been established, as well as a correlation between these properties and magnetic characteristics, these relationships being applicable to estimating the residual life of a material under cyclic loading. The coercive force measured on minor magnetic hysteresis loops in weak fields (the Rayleigh region) continuously rises as the number of cycles (accumulated plastic deformation) grows, and its behaviour qualitatively corresponds to the inverse dependence of residual elongation for the same loading conditions.

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