The Application of Magnetic, Electromagnetic-Acoustic and Eddy-Current Methods to the Assessment of Plastic Deformation under Cyclic Loading of Annealed Medium-Carbon Steel

Eduard S. GORKUNOV [1], Roman A. SAVRAI [1], Alexei V. MAKAROV [1],
Sergei M. ZADVORKIN [1], Leonid Kh. KOGAN [2]
[1] Institute of Engineering Science, RAS (Ural Branch)
34 Komsomolskaya street, GSP-207, 620219, Ekaterinburg, Russia
Tel: +7 (343) 3744725, Fax: +7 (343) 3745330
E-mail: ges@imach.uran.ru, Web: http://www.imach.uran.ru
[2] Institute of Metal Physics, RAS (Ural Branch)
18 Sofyi Kovalevskoy street, GSP-170, 620219, Ekaterinburg, Russia
Tel: +7 (343) 3740230, Fax: +7 (343) 3745244
E-mail: physics@imp.uran.ru, Web: http://www.imp.uran.ru

Abstract

The influence of fatigue stressing of annealed medium-carbon steel (with 0.45 wt. % of carbon) on the change of magnetic, electromagnetic-acoustic and eddy-current characteristics of the steel has been investigated. It has been shown that the coercive force, residual magnetic induction and the velocity of acoustic wave are sensitive to both large and small plastic deformations and that the readings of the eddy-current instrument are highly sensitive to small and mediate deformations accumulated under fatigue loading. The residual mechanical properties of the steel after cyclic loading have been established, as well as a correlation between these properties and the magnetic and eddy-current characteristics. The feasibility of magnetic, electromagnetic-acoustic and eddy-current nondestructive testing of accumulated plastic deformation and estimating of residual material life under cyclic loading has been demonstrated.

Keywords: Magnetic, electromagnetic-acoustic and eddy-current characteristics, Low-cycle fatigue, Accumulated plastic deformation, Residual mechanical properties, Nondestructive testing

1. Introduction

In most machines and structures, components operate under conditions of cyclically changing loads with regularly or irregularly alternating cycles and different levels of stresses in the cycles. The level of stresses in different regimes may correspondingly vary over a wide range and exceed both fatigue limit and yield stress of a material. As a result, plastic deformations arise in parts. This factor substantially complicates the study of fatigue resistance, the prediction of durability and the determination of residual life, and it requires a large amount of experimental data and full-scale tests. In this connection, the application of nondestructive test methods is very promising. Among the magnetic characteristics, coercive force can be selected as one used for evaluating the physical and mechanical properties of a material under deformation. Information on the possibility of using other parameters, in particular, residual magnetic induction[1,2], Barkhausen noise[3,4] is also available. The efficiency of the eddy-current method used for detecting the initial stages of fatigue damage and inspecting articles operating under conditions of cyclic loading was demonstrated[5]. The aim of this work is to investigate the effect of the fatigue stressing of annealed medium-carbon steel (with 0.45 wt.% of carbon) during low-cycle fatigue on the change of magnetic, electromagnetic-acoustic and eddy-current characteristics of the steel.

2. Experimental procedure and material

Commercially 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 to room temperature with an oven. 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 a voltage of 25 V for 6 minutes.

Cyclic loading of the specimens was carried out with a controlled value of total strain $\varepsilon_{tot}=2\varepsilon_a=\varepsilon_{el}+\varepsilon_{pl}=0.0076$ (where ε_a is strain amplitude, ε_{el} is the elastic part of strain, ε_{pl} is the plastic part of strain), pulsating deformation cycle, triangular change of strain amplitude and a 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 N=5, 10, 50, 200, 400 cycles. The value of accumulated plastic strain was calculated from the expression $\varepsilon_\Sigma = \ln(l_f/l_0)$, where l_0 is the initial gauge length and l_f is the gauge length of a specimen after cyclic loading. After fatigue stressing with a given number of cycles and measuring the physical characteristics, the specimens were subjected to tensile testing in order to determine residual mechanical properties. Cyclic loading and tensile testing were conducted on the Instron 8801 servohydraulic testing machine.

Magnetic characteristics were measured for the 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 the 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 with the use of the Remagraph C-500 magnetic measuring instrument.

The propagation velocity of elastic waves in specimens subjected to cyclic loading was measured via the electromagnetic-acoustic conversion method using the resonance technique. A zero symmetric mode of longitudinal normal elastic waves was excited with through-type probes. In the case of relatively thin rods in the low-frequency limit, the velocity of this mode is $V = \sqrt{E/\rho}$, where E is Young's modulus and ρ is the material density[6]. The scheme of the experiment was described[7].

The electromagnetic parameters were measured at a frequency of f=36 kHz on a laboratory mock-up of an eddy-current instrument and an attachable transformer-type transducer with a pot core connected differentially. An attachable eddy-current transducer with a flat end surface and a localization area 5-6 mm in diameter was used[8].

3. Results and discussion

The initial annealed state is characterized by minimal values of the coercive force, see the table. Under cyclic loading, increasing structural imperfection density is accompanied by increasing values of the critical fields of interaction between domain boundaries and defects[9]. This results in the growth of major coercive force values (fig. 1a). 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 $h_{max}<H_{critical}$), 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 $H_{critical}\approx h_{max}$,.

Table. The values of the coercive force (h_C, H_C), residual magnetic induction (b_r, B_r), propagation velocity of a longitudinal acoustic wave V and the readings α of the eddy-current instrument for the steel under study in the initial annealed state (N=0, 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)		V, m/s	α, points
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	5395	93

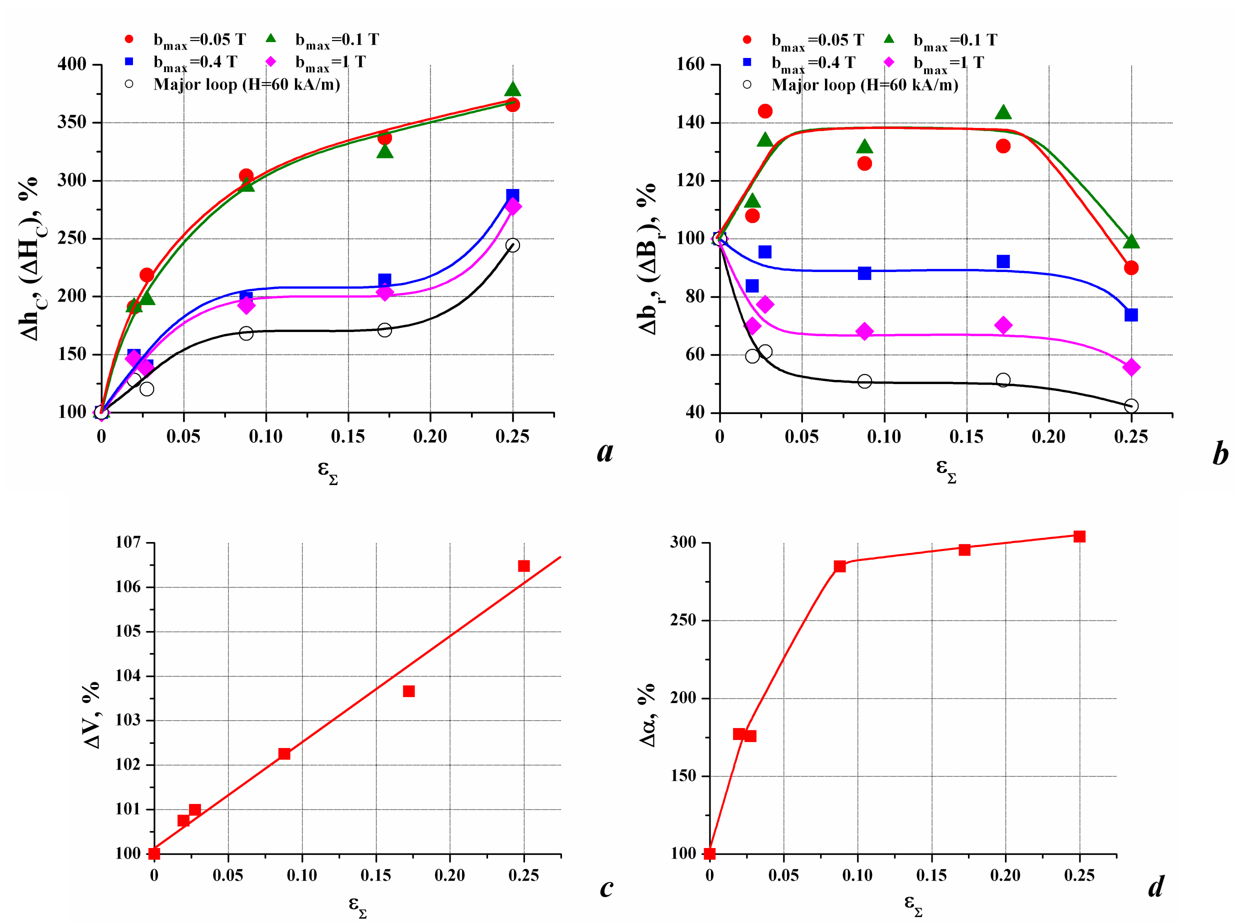

Fig. 1. Relative change of the coercive force (*a*), residual magnetic induction (*b*), the propagation velocity of a longitudinal acoustic wave (*c*) and the readings of the eddy-current instrument (*d*) as dependent on the accumulated plastic strain for the steel under study. The values of the physical characteristics for the steel in the initial annealed state are taken to be 100% (see the table).

Under alternating magnetization in stronger fields, one can see the stabilization of the coercive force values as the accumulated plastic strain varies between 0.07–0.1 and 0.15–0.17. 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[9]. Further deformation is again accompanied by the growth of the 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”[10].

In the early stage of deformation, at accumulated plastic strain up to 0.07–0.1, 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 strain up to 0.02–0.03) they increase for the minor loops corresponding to the maximal magnetic induction b_{max}=0.1 and 0.05 T (fig. 1b).

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[10]. 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 do 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 at accumulated plastic strain up to 0.15–0.17. 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[10]. These leakage fields are directed oppositely to the magnetization field, and this finally leads to decreasing residual magnetic induction.

During the entire deformation process, the propagation velocity of a longitudinal acoustic wave increases (fig. 1c), although this velocity must decrease with an increase in the imperfection density and level of macrostresses caused by straining[6]. In structural terms, the elastic moduli for metals are low-sensitivity characteristics, and they change only slightly under severe cold deformation (except for cases when a strain texture is formed). Increasing velocity V under uniaxial tension can be explained by decreasing material density[11] and the formation of an axial crystallographic texture with the <110> texture axis aligned with the loading axis[12]. As is known from[13], Young’s modulus along the <110> crystallographic axis for iron and its alloys is larger than that for isotropic polycrystals.

The material in the initial annealed state is characterized by minimum readings of the eddy-current instrument. During the initial stage of deformation, the abrupt increase in the signals of the eddy-current transducer corresponds to a total plastic strain of 0.07–0.10 (fig. 1d). The further deformation is accompanied by a weak increase in the readings of the eddy-current instrument until the end of the deformation process.

It was shown[14] that, during plastic deformation, changes in the density of dislocations in a metallic material substantially affect the values of the eddy-current parameter. At the initial stage of deformation in the region of low-cycle fatigue, the density of dislocations increases abruptly; subsequently, its growth slows down substantially. Thus, the observed character of variations in the readings of the eddy-current instrument corresponds to changes in the density of dislocations during the deformation of the steel.

Figure 2 shows correlations allowing us to determine changes in the residual strength (0.2% proof strength $S_{p0.2}$, ultimate tensile strength S_u, fracture stress S_{tot}) and plasticity (uniform elongation δ_u, total elongation δ_{tot}) characteristics using the readings α of the eddy-current instrument. The experimental results have also offered analytical equations relating magnetic characteristics ($h_{C\,0.05}$, $h_{C\,0.1}$) to residual (after cyclic loading) plasticity characteristics (δ_u, δ_{tot}), namely (δ is measured in % and h_C in A/m, R being the correlation coefficient),

$$\delta_u = 27.5927 - 0.43545 \cdot h_{C\,0.05}, \qquad R = -0.989;$$

$$\delta_{tot} = 48.43112 - 0.71935 \cdot h_{C\,0.05}, \qquad R = -0.986;$$

$$\delta_u = 27.01901 - 0.2102 \cdot h_{C\,0.1}, \qquad R = -0.993;$$

$$\delta_{tot} = 47.26525 - 0.34447 \cdot h_{C\,0.1}, \qquad R = -0.982$$

Thus, using the dependences obtained, one can estimate the residual life of a material subjected to low-cycle fatigue stressing.

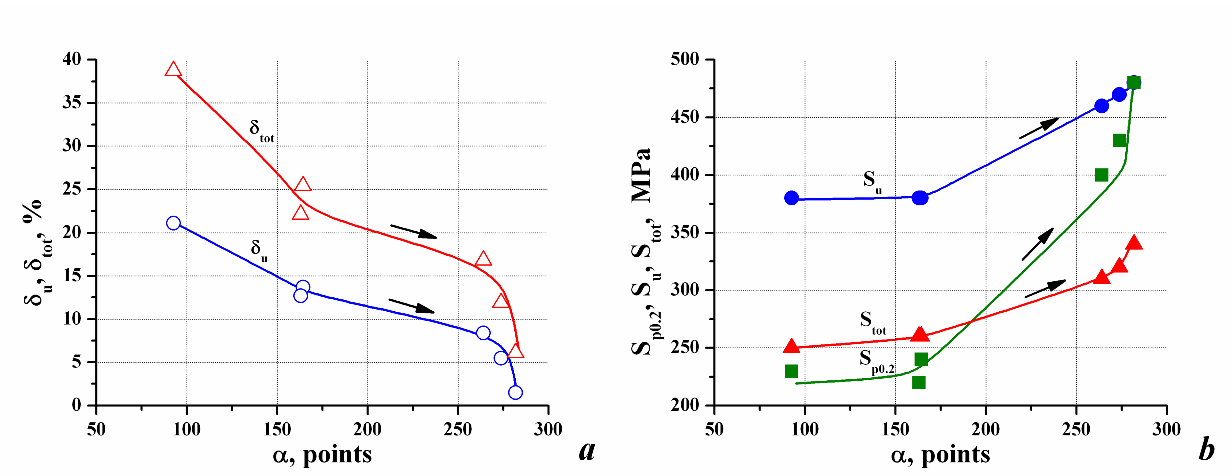

Figure 2. Correlations between the residual (after cyclic loading) strength and plasticity properties of the steel under study and the readings of the eddy-current instrument. The arrows show an increase in the number of loading cycles (accumulated plastic deformation).

4 Conclusion

(1) The dependences describing changes in the coercive force, residual magnetic induction for the major and minor magnetic-hysteresis loops, velocity of a longitudinal acoustic wave and readings of the eddy-current instrument as functions of the value of accumulated plastic strain have been obtained for cyclically loaded specimens of annealed medium-carbon steel (with 0.45 wt. % of carbon) in the low-cycle fatigue region. These dependences show that the plastic strain accumulated during cyclic loading can be tested via the values of these parameters.

(2) The character of changes in the residual (after cyclic loading) mechanical properties of annealed medium-carbon steel as functions of the value of the accumulated plastic strain has been established, as well as the correlations between these properties and the magnetic and eddy-current characteristics, these relationships being applicable to estimating the residual life of a material under cyclic loading.

References

[1] Shah M.B., Bose M.S.C., Magnetic NDT technique to evaluate fatigue damage, Physica status solidi (a), 1984, Volume 86, Number 1, p275-281.

[2] Muzhitskii V.F., Popov B.E., Bezlyud’ko G.Ya., Zarudnyi V.V., Levin E.A., Magnetic monitoring of the stress-strain state and residual safe life of the steel structures of hoisting cranes, Russian Journal of Nondestructive Testing (English translation), 1996, Volume 32, Number 2, p97-102.

[3] Donzella G., Granzotto S., Some experimental results about the correlation between Barkhausen noise and the fatigue life of steel specimens, Journal of Magnetism and Magnetic Materials, 1994, Volume 133, p613-616.

[4] Palma E.S., Mansur T.R., Ferreira Silva Jr S., Alvarenga Jr A., Fatigue damage assessment in AISI 8620 steel using Barkhausen noise, International Journal of Fatigue, 2005, Volume 27, p659-665.

[5] Bystrushkin G.S., Possibility of determination of an early stage of fatigue damage of chromium steel via the eddy-current method, Defektoskopiya, 1968, Number 5, p1-7 (in Russian).

[6] Ed. Aleshin N.P., Acoustic methods of testing materials, Moscow, Mashinostroenie, 1989, 456 p. (in Russian).

[7] Komarov V.A., Revina N.A., Application of a resonance electromagnetic-acoustic transformation for testing the quality of heat treatment of martensitic steels, Defektoskopiya, 1984, Number 2, p66–73 (in Russian).

[8] Makarov A.V., Gorkunov E.S., Kogan L.Kh., Kolobylin Yu.M., Korshunov L.G., Osintseva A.L., Features of electromagnetic methods for testing the wear resistance of medium-carbon structural steel subjected to laser or bulk hardening and tempering, Russian Journal of Nondestructive Testing (English translation), 2006, Volume 42, Number 7, p443-451.

[9] Vicena F., On the influence of dislocations on the coercive force of ferromagnetics, Czechosl. Journ. Phys., 1955, Volume 5, Number 4, p480-499 (in Russian).

[10] Mikheev M.N., Gorkunov E.S., Magnetic methods of nondestructive testing and structure analysis, Moscow, Science, 1993, 252 p. (in Russian).

[11] Gorkunov E.S., Smirnov S.V., Rodionova S.S., Effect of plastic deformation under hydrostatic pressure on the damageability and magnetic parameters of low-carbon 3sp steel, Fizicheskaya Mezomekhanika, 2003, Volume 6, Number 5, p101-108 (in Russian).

[12] Wassermann G., Grewen J., Texturen metallischer Werkstoffe, Berlin, Springer, 1962.

[13] Ed. Samsonov G.V., Properties of elements, Part 1: physical properties, Moscow, Metallurgiya, 1976, 600 p. (in Russian).

[14] Sandovskii V.A., Uvarov A.I., Tereshchenko N.A., Effect of plastic deformation and annealing of armco-iron on the output of an attachable eddy-current transducer, Russian Journal of Nondestructive Testing (English translation), 1999, Number 3.