EFFECTS OF ACCUMULATED TORSIONAL STRAIN AND DAMAGE ON THE MAGNETIC PROPERTIES OF STEEL

E.S. Gorkunov, S.V. Smirnov, D.I. Vychuzhanin, S.Yu. Mitropolskaya
The Urals Branch of the Russian Academy of Sciences, Yekaterinburg, Russia.

Abstract: The effect of shear strain and accumulated damage on magnetic properties was studied on cylindrical steel rods subjected to torsion. The correlations obtained make it possible to evaluate the shear strain and current damage of metal, as well as to estimate the residual lifetime of an article under torsion, provided its magnetic parameters are available.

Introduction: It is known that during plastic deformation, particularly in course of torsion, defects of metal continuity are generated (e.g. micropores, microcracks, vacancies, etc). The defects are observed as early as at early stages of plastic deformation. The formation of discontinuities is accompanied by partial relaxation of elastic energy [1], which leads to changes in the magneto-elastic energy of ferromagnetic material in the regions adjacent to the defects. This phenomenon is likely to affect the magnetic parameters of materials.

Results: The influence of shear strain rate and torsion-induced damage on the magnetic parameters of metals was investigated. Analytical relationships were obtained for magnetic coercivity (from both major and minor hysteresis loops) as a function of strain and damage accumulated by a material.

Commercial steel with 0.45% carbon content was studied. Measurements were made on hot-rolled rods 5mm in diameter. The test unit utilized made it possible to take magnetic parameters in the run of loading. Magnetic properties were determined from both major and minor cycles of magnetic hysteresis. As distinct from [2], all the magnetic properties were measured as a function of internal magnetic field. Measurements were made of the following magnetic parameters: maximum magnetic permeability μ_{max}, coercivity H_c (h_c) and residual induction B_r (b_r) from major (H_{max}= 60 kA/m) and minor hysteresis loops during magnetization in medium (b_{max}=0.4 T) and low (b_{max}=0.1 T) magnetic fields.

The degree of shear strain Λ under torsion was estimated under the assumption that the sample cross-section radius is not subjected to distortion in course of loading [3], thus the shear strain degree on the surface of the sample is

$$\Lambda = \mathrm{tg}\varphi, \tag{1}$$

where φ is the angle between the printed mark on the sample surface and its generating line. The average degree of shear strain along the cross-section of the sample was calculated as [3]

$$\widetilde{\Lambda} = \frac{1}{\pi R^2}\int_0^{2\pi}\int_0^R \frac{r}{R} tg\varphi \cdot r\, d\varphi\, dr = \frac{2}{3}\Lambda , \tag{2}$$

where R is the radius of the sample, r is its current radius ranging from 0 to R.

The average integral degree of accumulated shear strain Λ_{int} was calculated by taking the summation over all the previous values of the strain degree.

The parameter of material damage ω is used in mechanics to indicate the development of deformational microdefects. According to the phenomenological theory of fracture [4], $\omega = 0$ before deformation, whereas $\omega = 1$ when a fracture crack emerges.

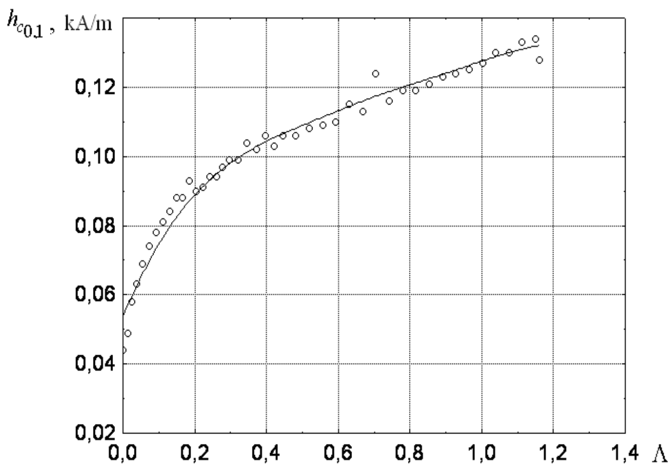
Since the state of strain was not subjected to changes in course of deformation, the parameter of material damage ω was calculated in accordance with the linear model by Kolmogorov for damage accumulation: [3] as

$$\omega = \int_0^{\Lambda} \frac{d\Lambda}{\Lambda_f}, \tag{3}$$

where Λ_f is the degree of shear strain at the moment of fracture.

As the strain degree rises, the magnetic hardness of steel increases, the coercive force and residual induction grow, while magnetic permeability decreases (Fig. 1 to 3).

a



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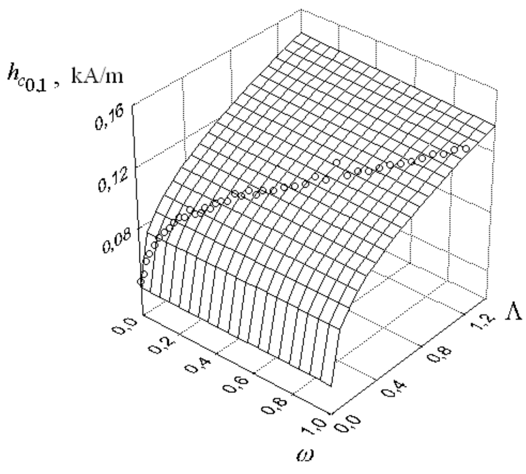

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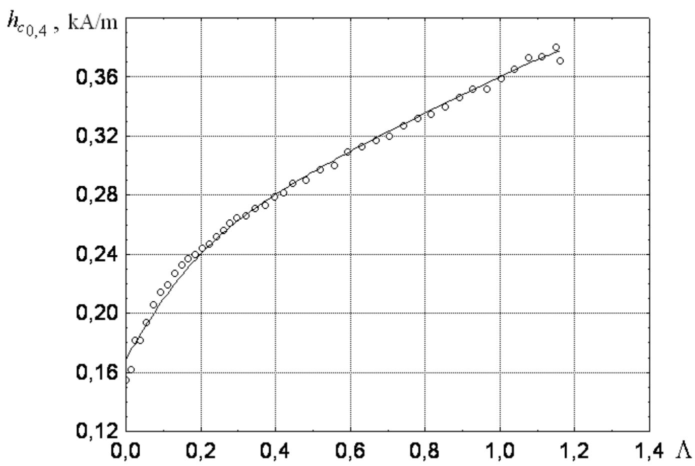

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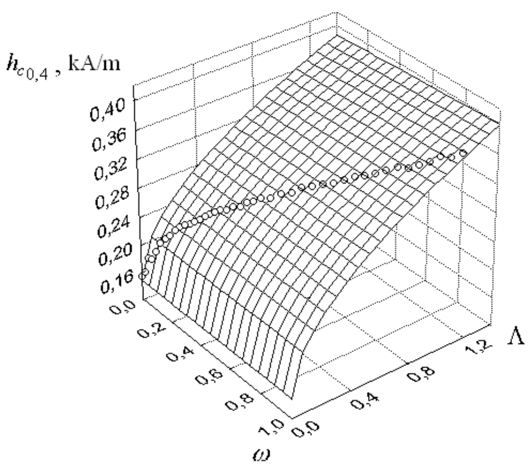

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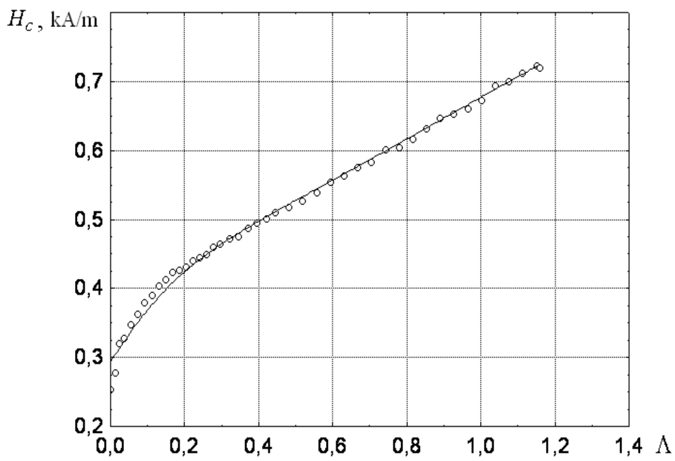

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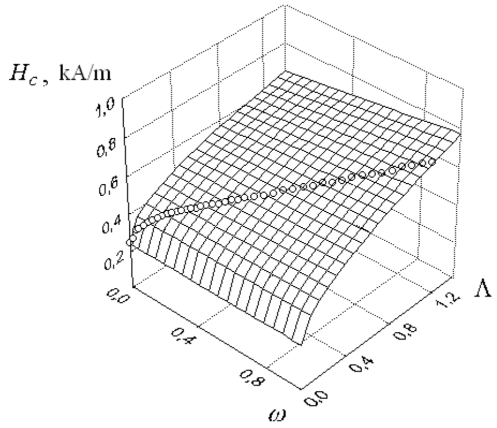
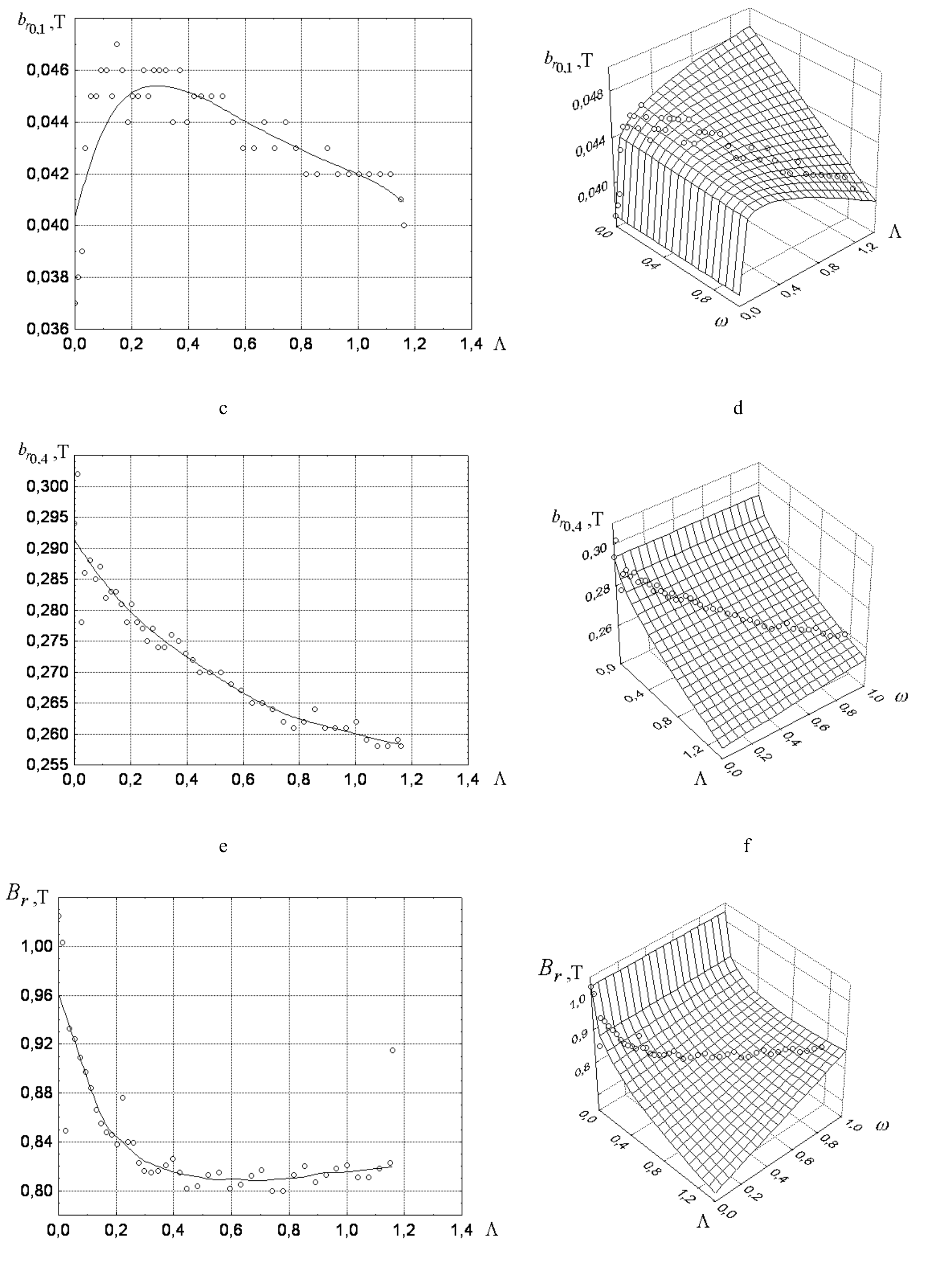


Fig. 1

a

b



$b_{r0,1}$,T
0,046
0,044
0,042
0,040
0,038
0,036
0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 Λ
c
$b_{r0,1}$,T
0,048
0,044
0,040
0,0 0,4 0,8 1,2 Λ
0,0 0,4 0,8 ω
d
$b_{r0,4}$,T
0,300
0,295
0,290
0,285
0,280
0,275
0,270
0,265
0,260
0,255
0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 Λ
e
$b_{r0,4}$,T
0,30
0,28
0,26
0,0 0,4 0,8 1,2 Λ
0,0 0,2 0,4 0,6 0,8 1,0 ω
f
B_r ,T
1,00
0,96
0,92
0,88
0,84
0,80
0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 Λ
B_r ,T
1,0
0,9
0,8
0,0 0,4 0,8 1,2 Λ
0,0 0,2 0,4 0,6 0,8 1,0 ω

Fig. 2

a b

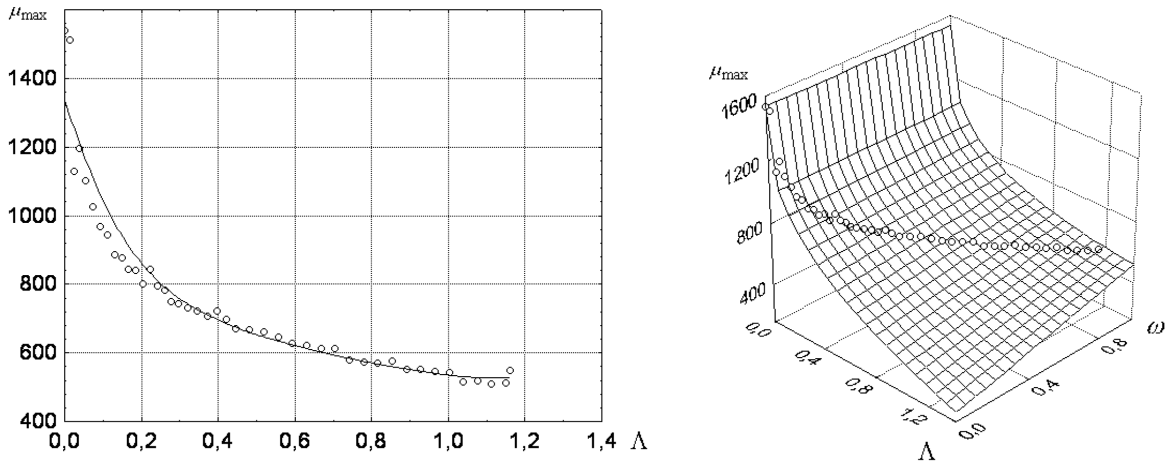


Fig. 3

This is indicative of hampered magnetization and magnetization reversal due to higher values of the critical fields of interaction between the domain boundaries and the defects in the metal structure.

Discussion: A number of factors influence magnetization reversal. A notable change in the magnetic characteristics occurs as early as at small values of strain degree. According to the model representations of the effect of dislocations on magnetization reversal, the coercive force is associated with the dislocation density as $H_c \sim \sqrt{N}$. Therefore the coercive force increases as the dislocation density grows at the initial stage of deformation.

The further increase in the values of magnetic characteristics results from the evolution of the dislocation and domain magnetic structures, which is associated with the formation of dislocation walls, as they are the effective areas for domain boundary pinning. Near the inclusions and in the regions of high microstress gradients there appears a disperse structure of 90^o magnetic domains, which is typified by critical fields approximately 1.5 times as great as those for magnetic structures with 180^o domains. As this occurs, these regions may be quite large in volumes.

Figures 1 to 3 show magnetic parameters as a function of strain degree. It is obvious that magnetic parameters measured under various magnetic field strengths make it possible to estimate the degree of plastic strain, as well as material damage associated with accumulation of microdefects. The results obtained reveal analytical relationships for magnetic characteristics as a function of the calculated parameter of material damage:

$$h_{c_{0,1}} = 0{,}04 + 0{,}0917 \cdot \Lambda^{0{,}384} - 0{,}0055 \cdot \Lambda \cdot \omega$$

$$h_{c_{0,4}} = 0{,}148 + 0{,}2 \cdot \Lambda^{0{,}485} + 0{,}009 \cdot \Lambda \cdot \omega$$

$$H_c = 0{,}24 + 0{,}35 \cdot \Lambda^{0{,}41} + 0{,}09 \cdot \Lambda \cdot \omega \qquad (4)$$

$$b_{r_{0,1}} = 0{,}037 + 0{,}0107 \cdot \Lambda^{0{,}177} - 0{,}0068 \cdot \Lambda \cdot \omega$$

$$b_{r_{0,4}} = 0{,}294 - 0{,}039 \cdot \Lambda^{0{,}593} + 0{,}0059 \cdot \Lambda \cdot \omega$$

$$B_r = 1{,}025 - 0{,}3 \cdot \Lambda^{0{,}33} + 0{,}124 \cdot \Lambda \cdot \omega$$

$$\mu_{max} = 1539 - 1185{,}7 \cdot \Lambda^{0{,}33} + 215{,}962 \cdot \Lambda \cdot \omega .$$

Conclusions: The result of the study performed demonstrates that it is possible to monitor torsion-induced shear strain and the deformation-related metal damage by means of magnetic characteristics measured on both minor and major loops of magnetic hysteresis. Knowing the parameters Λ and ω, one can calculate the remaining lifetime of an article using corresponding mechanical models. This work has been conducted with the financial support from the RFFR, grants 03-01-00794 and 04-01-96112.

References: 1. Low, J.R. Brittle fracture as related to microstructure. In: The Structure of Metals and Properties. M., National Science and Technology Publisher for Literature on Ferrous and Non-Ferrous Metallurgy. 1957, p. 170 – 189.
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3. Kolmogorov, V. L. Stress, strain, fracture. M., Metallurgia, 1970, 230 p.
4. Kolmogorov, V. L. Mechanics of metal forming. M., Metallurgia, 1986, 688 p.

Captions

Fig. 1. Coercivity measured on minor (a, b: at $b_{\max} = 0{,}1$ T; c, d: at $b_{\max} = 0{,}4$ T) and major (e, f) cycles of magnetic hysteresis as a function of shear strain degree and the parameter of damage for 0.45% C steel samples.

Fig. 2. Residual induction measured on minor (a, b: at $b_{\max} = 0{,}1$ T; c, d: at $b_{\max} = 0{,}4$ T) and major (e, f) cycles of magnetic hysteresis as a function of shear strain degree and the parameter of damage for 0.45% C steel samples.

Fig. 3. Maximum magnetic permeability as a function of shear strain degree and the parameter of damage for 0.45% C steel samples.