MAGNETIC TESTING OF STRESSES AND STRAINS IN AREAS OF STRUCTURAL MACROHETEROGENEITIES IN STEEL ARTICLES

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The estimation of stresses and strains arising during operation in machine parts and structural members containing layers with different physical properties is an urgent problem attracting the attention of researchers dealing with nondestructive testing. There is a need to inspect the state of every layer in order to estimate its further efficiency and/or repairability. This approach is based on the idea that, in magnetic terms, steel parts can be considered to contain two layers, one of which is hard magnetic and the other is soft magnetic. The number of peaks on the curve representing differential magnetic permeability μ_d as dependent on the switching field corresponds to the number of layers differing in magnetic properties.

The potentialities of magnetic technique in estimating stresses appearing in the hardened surface layer and in the core of an axisymmetric article are discussed in this paper, with cylindrical specimens made of steels 45 and 20 subjected, respectively, to laser thermal hardening and gas carburizing taken as examples. The depth of hardened layers was up to 1.5 mm in specimens with a gage length of 7 mm.

The field dependence of differential magnetic permeability

$$\mu_d = \lim_{H \to 0} \frac{\Delta B}{\Delta H} = \frac{dB}{dH}$$

was determined by differentiating the descending branches of the major loops with respect to the field in the range between +60 and –60 kA/m (the figures show only the portions of the field dependences that have maximum permeability). The hardness (HV), microstructure (×400) and magnetic properties of the hardened surface layers and cores of the specimens are provided in Table 1. Fig.1 shows differential magnetic permeability μ_d as dependent on the switching field H for three instances studied. Laser surface hardening with subsequent self-tempering is seen to result in the formation of sorbite with a hardness of 285 HV in the surface layer of steel 45. The highest surface hardness of up to 1200 HV (70 HRC) was attained on steel 20 after carburizing to the depth of 1.5 mm and water quenching with the formation of coarse-acicular martensite; due to it a maximum of μ_d can be observed in fields near 3 kA/m. Low-carbon martensite with a hardness of up to 550 HV was found in the core, and the corresponding peak of differential magnetic permeability was observed in fields near 1.1 kA/m. Significantly less hardening was attained for steel 20 after the same carburizing conditions, but with subsequent oil quenching. In this case, troostite with hardness of up to 500 HV was produced in the surface layer, while the peak on the field dependence of differential magnetic permeability corresponding to this layer was observed in a magnetic field of about 1.2 kA/m.

Table 1 Hardness, structure and magnetic properties of surface hardened steels

Steel	Type of surface hardening	Area	Hardness, HV	Structure	$H(\mu_{dmax})$, kA/m	μ_{dmax}, $\times 10^{-3}$
45	Laser hardening	Surface	285 HV	sorbite	1.3	1.5
		Core	220 HV	ferrite+pearlite	0.6	2.3
20	Carburization and oil quenching	Surface	500 HV	troostite	1.2	1.3
		Core	200 HV	ferrite+pearlite	0.4	3.5
20	Carburization and water quenching	Surface	1200 HV	martensite	3.0	0.7
		Core	550 HV	martensite	1.1	0.7

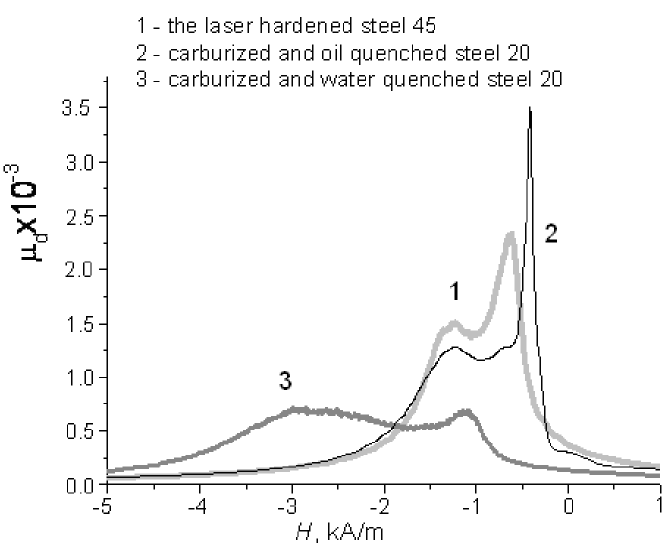
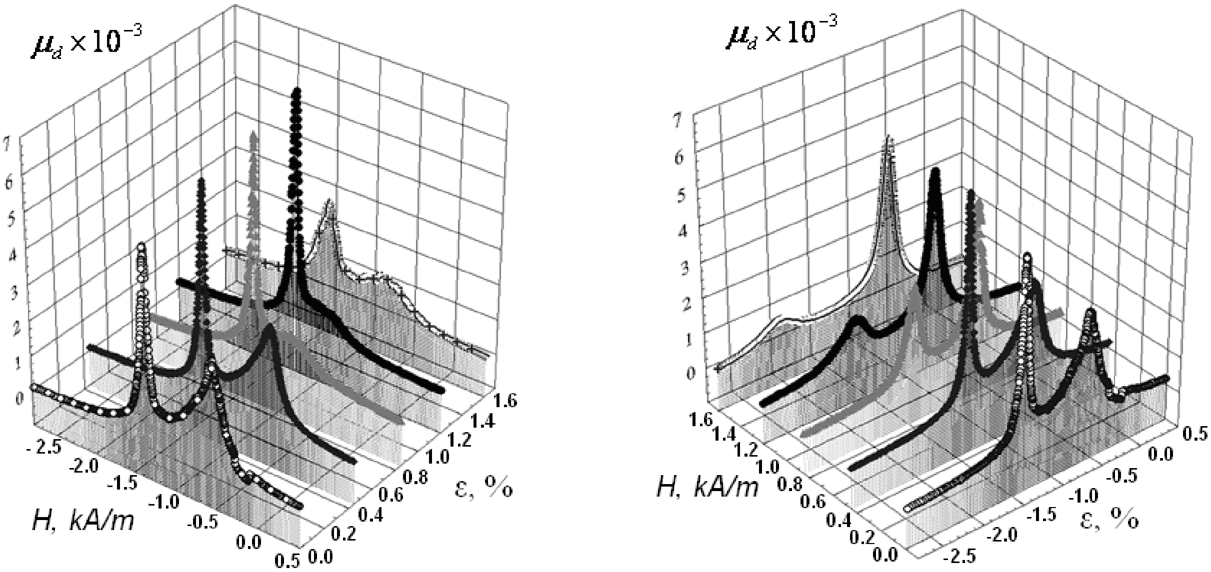


Fig. 1 The field dependence of differential magnetic permeability: laser hardened steel 45 specimen (1); carburized and oil quenched steel 20 specimen (2); carburized and water quenched steel 20 specimen (3).

The effect of elastic-plastic tension on the magnetic properties of laser hardened steel 45

It has been found (Figs 2, 3) that the considerable shifts of the μ_d peaks toward the range of stronger magnetic fields are observed at stresses of 390 to 400 MPa approximating to the yield stress of the core (first peak I), and stresses of 950 to 1000 MPa approximating to the yield stress of the surface layer (peak II). The shifts are accompanied by a simultaneous abrupt decrease in peak heights. It has been revealed that the loss of the bimodal behaviour of the dependence $\mu_d(H)$ after unloading (Fig. 2b) suggests that the surface-hardened material nears fracture.



a *b*

Fig. 2 The field dependence of differential magnetic permeability for laser hardened steel 45 specimens as a function of elongation: measurements under loading (a) and after unloading (b).

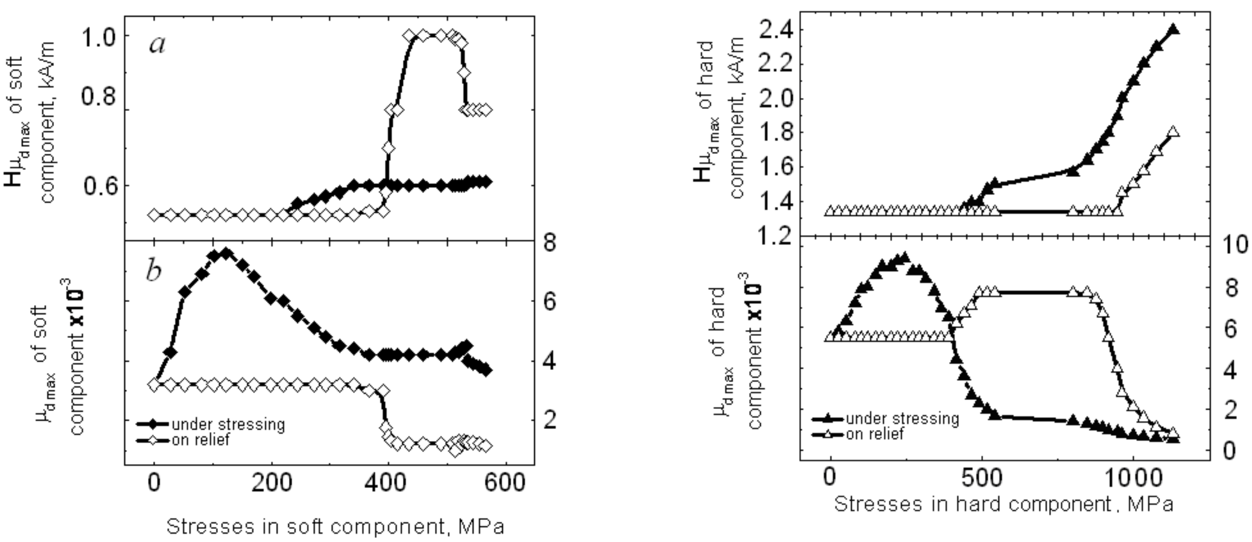


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Fig. 3 The peak field and peak height of maximum differential magnetic permeability in the core (a) and in the surface layer (b) of a laser hardened specimen vs tensile stress: under loading (black spots) and after unloading (empty spots).

The effect of monotonic elastic tension and compression on the magnetic properties of carburized and oil quenched specimens made of steel 20

The mechanical properties after carburizing and oil quenching are σ_B = 900 MPa, $\sigma_{0.2}$ = 615 MPa. Figures 4 and 5 feature the effect of compression stress (up to 200 MPa) and tension stress (up to 400 MPa), respectively, on the field dependence of differential magnetic permeability. Elastic compression is seen to cause a significant decrease in the core peak height, while the carburized surface peak remains unchanged. The drop of differential magnetic permeability μ_d in the field of about 0.4

kA/m amounts to 70%, while in the field of 0.7 to 0.8 kA/m a 25% decrease in μ_d from the initial value is observed, the μ_d estimation precision being 12%. Similar results were obtained for all the specimens of this group.

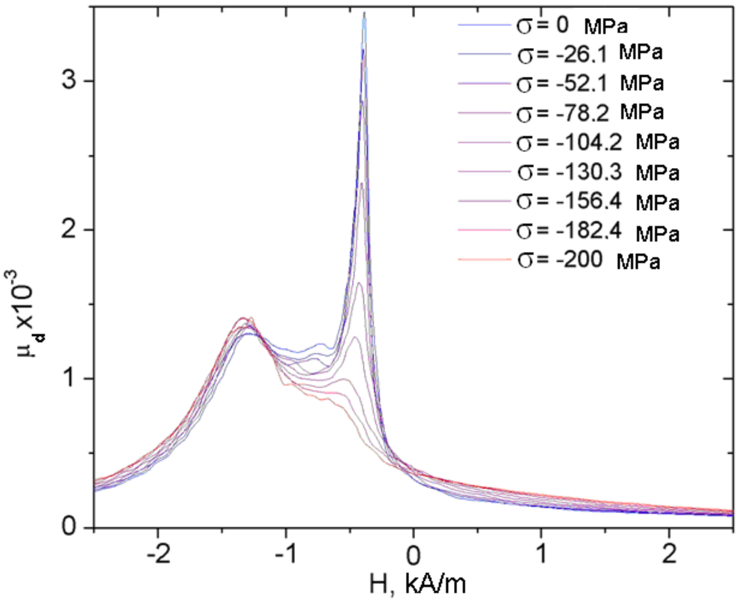

Fig. 4 The effect of elastic compression on the field dependence of differential magnetic permeability for carburized and oil quenched steel 20 specimens.

The differential magnetic permeability of the core also decreases under elastic compression, though less actively (Fig.5). This is accompanied by a 40% increase of μ_d from the initial value in fields of 0.7 to 8 kA/m. The surface peak and the core peak have approximately the same heights under tensile stress of 400 MPa. Carburizing is known to produce residual compressive stress of up to 200 MPa in the surface layer. The applied tension stress is likely to compensate the residual compressive stress in the carburized layer. Similar results were obtained for all the specimens of this group.

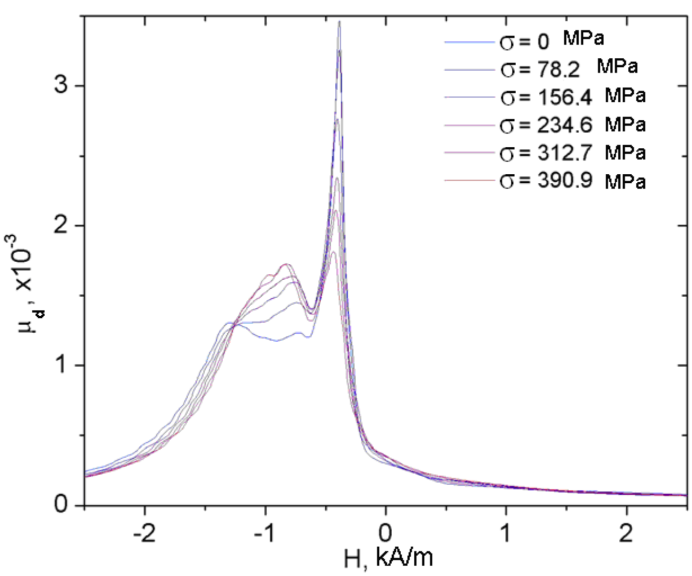

Fig. 5 The effect of elastic tension on the field dependence of differential magnetic permeability for carburized and oil quenched steel 20 specimens.

The in-situ magnetic measurements of carburized and water quenched steel 20 under elastic compression and tension have failed to reveal any changes in the magnetic permeability of the hardened layer. It is supposed to have high magnetic hardness, so that elastic stresses ranging between –200 and +350 MPa have no effect on its fairly stable magnetic state.

Conclusion

Significant shifts of the magnetic permeability peaks toward stronger magnetic fields and rapid decreases in peak heights result from the involvement of different layers of laser hardened steel 45 in plastic deformation and occur in strictly defined sequence as the stress corresponding to the yield limit of each layer is reached. The results revealed may be useful for the diagnostics of critical loading conditions. When analyzing the field dependence of differential magnetic permeability, one can determine the elastic loading scheme for carburized and oil quenched steel 20, namely, elastic compression results in a significant decrease of magnetic permeability μ_d in magnetic fields of 0.7 to 0.8 kA/m, while the elastic tension leads to a substantial increase of permeability in the same fields.

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