ISSN 1061-8309, Russian Journal of Nondestructive Testing, 2015, Vol. 51, No. 10, pp. 610–615. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © A.P. Nichipuruk, A.N. Stashkov, M.S. Ogneva, A.V. Korolev, A.A. Osipov, 2015, published in Defektoskopiya, 2015, Vol. 51, No. 10, pp. 19–23.

MAGNETIC METHODS

Induced Magnetic Anisotropy in Low-Carbon Steel Plates Subjected to Plastic Deformation by Stretching

A. P. Nichipuruk[a], **A. N. Stashkov**[a], **M. S. Ogneva**[a], **A. V. Korolev**[a], **and A. A. Osipov**[b]
[a] *Institute of Metal Physics, Ural Branch, Russian Academy of Sciences, Yekaterinburg, Russia*
e-mail: nichip@imp.uran.ru, stashkov@imp.uran.ru, ogneva@imp.uran.ru, korolyov@imp.uran.ru
[b] *Institute of Applied Physics, Belarussian Academy of Sciences, Minsk, Belarus*
e-mail: osipov@iaph.bas-net.by

Received July 10, 2015

Abstract—Experimental studies of induced magnetic anisotropy in plastically deformed low-carbon steel were carried out. The measurements were performed on samples in the form of discs. The maximum energy of the induced magnetic anisotropy was observed at a relative elongation of ~12% upon an increase in the plastic deformation of samples. At higher degrees of deformation the energy of the induced magnetic anisotropy is reduced, which indicates a decrease in the residual mechanical stresses in the material.

Keywords: low-carbon steel, plastic deformation, induced magnetic anisotropy, residual stresses

DOI: 10.1134/S1061830915100095

INTRODUCTION

Evaluation of plastic deformation and internal stresses in constructions made of low-carbon and lightly doped steel is an urgent tasks of nondestructive testing and, in particular, magnetic structurescopy. A number of papers have been published on this topic [1–8]; however, the behavior of induced magnetic anisotropy related to the residual mechanical stresses (after the plastic deformation) is not still clear.

In our previous works [9–12], the formation of an easy-plane (EP) magnetic texture perpendicular to the pre-stretching axis as a result of plastic deformation was experimentally confirmed.

In [9, 10] simulation of the ratio of compressed and stretched metal grains after plastic deformation by stretching based on coercive force and residual magnetization measurements was carried out. Formation of LP-type anisotropy can be explained using the data from these experiments. Magnetic anisotropy in the massive solid samples was measured by an attached primary converter; the results were reported in [11, 13]. This method not only has some advantages from the practical point of view, but also a number of disadvantages, such as a non-uniform magnetizing field and the influence of the sample shape and dimensions on the measured parameters.

Magnetic-anisotropy measurements as a rule are carried out using anisometers, with the samples being disc shaped. In contrast to an infinitely thin disc, the definite thickness and, hence, demagnetizing factor of the real samples should be taken into account when estimating the induced anisotropy. It is noteworthy that the demagnetizing factor that is measured along the sample plain is constant regardless of the angle.

With the results of the magnetization being constant, the angular dependencies of magnetic particles can be compared.

In [14] the energy of the induced magnetic anisotropy was measured directly, in [15] the difference of the coercive force values was determined, and in [11] the behavior of the differential magnetic permeability in the limit of the hysteresis loop measured along and perpendicular to the stretching axis of the low-carbon steel samples was described. Despite the attempt to estimate the magnetic parameters during plastic deformation caused by stretching [11, 12], these estimates were hampered by scale parameters, such as the sample shape and dimensions, as well as by the complexity of the data treatment technique. Therefore, the problem of the determination of magnetoisotropic properties at high (more than 10%) plastic deformations is still unsolved.

In this work induced magnetic anisotropy as a function of plastic deformation in low-carbon steel plates was measured by different techniques. The value of the coercive-force anisotropy along and perpendicular to the pre-stretching direction has been compared with the value of the magnetization anisotropy.

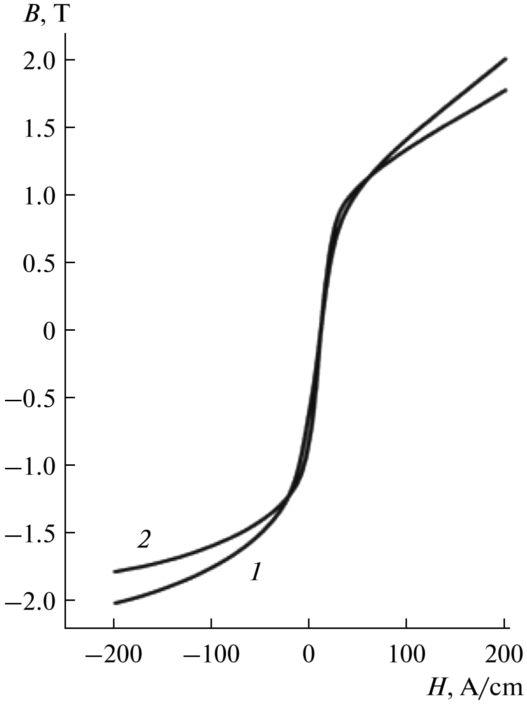

Fig. 1. The rising branches of the limit magnetic-hysteresis loops along (curve *1*) and perpendicular (curve *2*) to a plate with 6% deformation.

MATERIALS AND METHODS

Flat experimental samples of the following dimensions were manufactured: length, 194 mm; width, 70 mm; and height, 1.4 mm. The working-area dimensions were 70 × 70 mm. The plates were manufactured of St20 carbon steel and were pre-annealed.

The samples were stretched using a testing machine within the 0–28% relative elongation range. After stretching or plastic deformation, discs with a diameter of 30 mm were cut out of the central parts of the plates. A disc was placed between the electromagnet poles. The strength of the electric field in the electromagnet gap was 215 A/cm and the tangential component of the field at the disc surface was approximately 35 A/cm. The normal component of the scattering field was registered by a Hall sensor mounted above the edge of the disc. The angular dependence of the magnetization was determined from the magnetic-scattering data.

The coercive force was measured using a magnetometric installation at a maximum magnetizing field of 1200 A/cm.

RESULTS AND DISCUSSION

Previously [11], the dependence of the differential permeability on the field on the limit hysteresis loop was determined along and perpendicular to the deformed plates of low-carbon steel. Let us return to this work to the difference of the energies that were spent for magnetization reversal in mutually perpendicular directions. Let us assume that the energy difference is determined by the magnetic anisotropy that is induced by plastic deformation.

The rising branches of the limit hysteresis loops for a plate that was subjected to stretching with a relative elongation of 6% are presented in Fig. 1. The energy of the induced magnetic anisotropy was calculated from the difference of the areas under the curves that were measured along and perpendicular to the plate. The same calculations were carried out for different deformation degrees with relative elongations of 4, 6, 15, 25, and 30%. The dependence of the calculated values on the degree of plastic deformation is presented in Fig. 2.

According to the results, the energy of the induced magnetic anisotropy substantially increased up to the relative elongation of 6–15% and then fell sharply. With some approximations, the values of the residual stress that arise in the plates after plastic deformation caused by stretching can be calculated from the

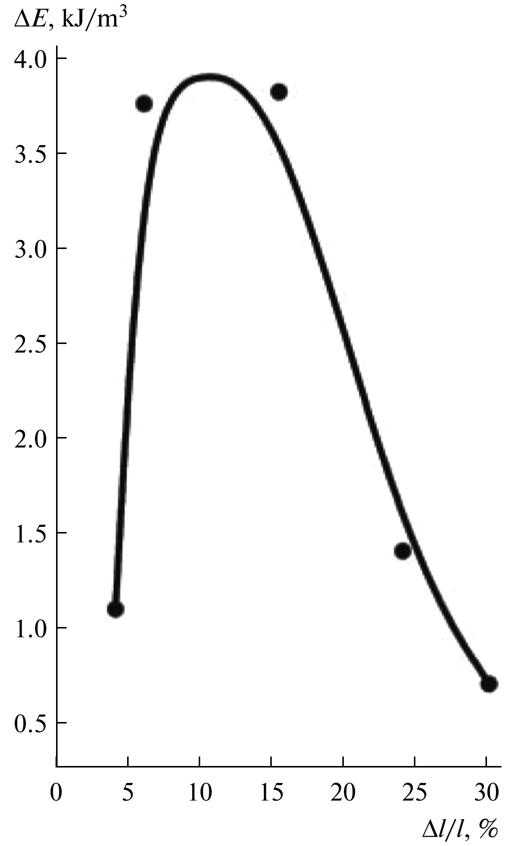

Fig. 2. The remagnetization energy difference along and perpendicular to the pre-stretching axis as a function of the relative elongation.

data that are presented in Fig. 2. The energy of the induced magnetic anisotropy was compared with the magnetoelastic energy of the residual stresses ($3/2\lambda_{100}\sigma$). According to the calculations, the residual stresses increased from ~38 to ~130 MPa at relative elongation of 4% and 6–15% respectively, and then decreased with the further increase of the plastic deformation. However, the reliability of these data is not satisfactory due to the side scattering of the magnetic flow around the electromagnet poles and the unaccounted influence of the gap between the poles and the plate.

Next, 30-mm discs that were cut from the central parts of the pre-stretched plates were tested. The angular dependences of the relative magnetization for disc-shaped samples placed into an external constant magnetic field of 215 A/cm are presented in Fig. 3; the internal field was approximately 35 A/cm. The experimental technique was described above.

EP-type magnetic anisotropy of samples with relative elongations of 6 and 12% is illustrated in Fig. 3. The minimum values of the scattering fields (magnetization) are observed along the pre-stretching axis of the plate (angles of 0, 180, and 360°) and the maximum values are seen along the perpendicular direction (angles of 90 and 270°). It is seen that the anisotropy value rises with the increase of the plastic deformation. The deviations of the values curve *1*, which correspond to the disc that was cut out of the initial plate are due to the measurement error. The relative difference of the magnetization along and perpendicular to the stretching axis as a function of relative elongation presented in Fig. 4 is based on these measurements. It was shown that induced magnetic anisotropy increases with an increase in the plastic deformation up to 10–12% and then decreases.

In addition, the coercive force along and perpendicular to the pre-stretching axis for different levels of plastic deformation was determined (Fig. 5).

The relative difference of the coercive forces as a function of the plastic deformation is illustrated in Fig. 6. It should be noted that the maximum relative difference is achieved at a deformations of approximately 10%.

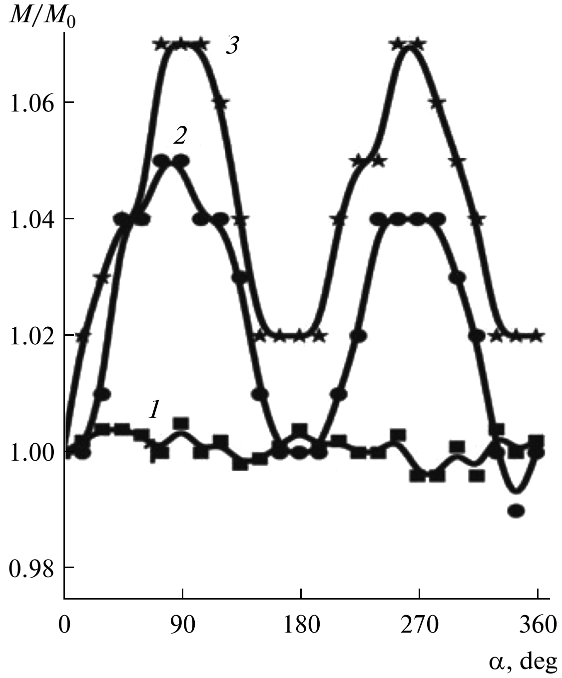

Fig. 3. The angle dependencies of the relative magnetization for the samples with different degrees of relative elongation: *1*, initial sample; *2*, relative elongation, 6%; *3*, 12%. M_0, magnetization along the pre-stretching axis.

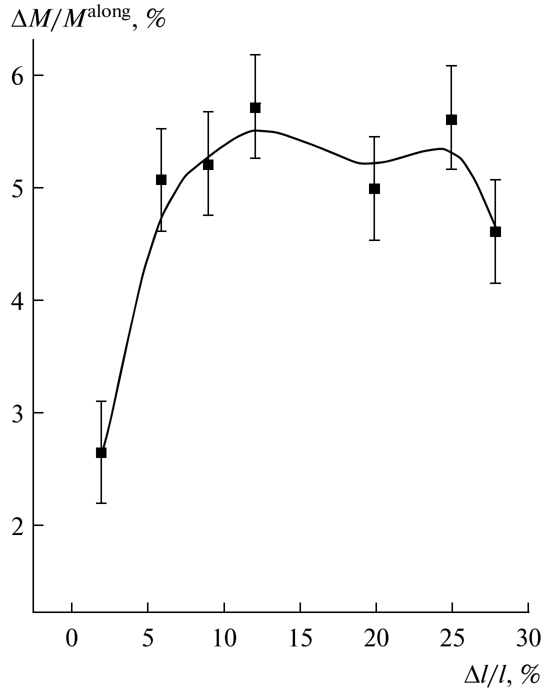

Fig. 4. The relative magnetization difference along and perpendicular to the stretching axis as a function of the relative elongation.

CONCLUSIONS

The following conclusions can be made based on this study:

1. Induced magnetic anisotropy increases with the degree of plastic deformation, with its maximum value being observed at a relative elongation of 10–15%. Anisotropy is thought to be formed by residual

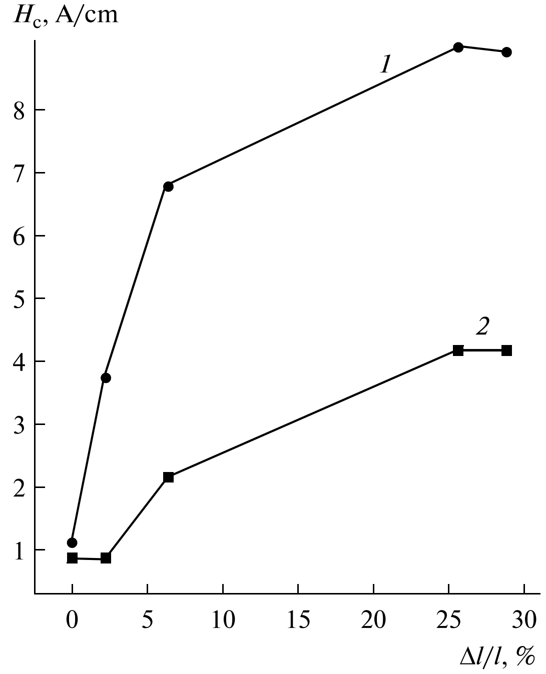

Fig. 5. The coercive force as a function of the relative elongation:
Curves *1* and *2*, measurements along and perpendicular to the pre-stretching axis, respectively.

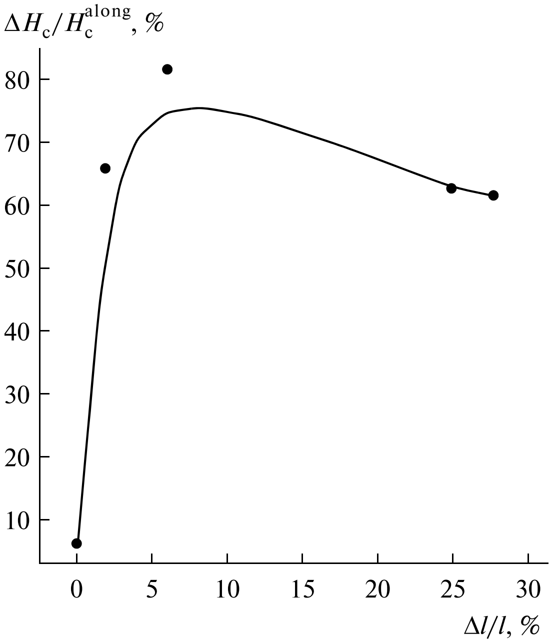

Fig. 6. The relative difference of the coercive force along and perpendicular to the pre-stretching axis as a function of relative elongation.

stresses (after plastic deformation); thus, it can be concluded that these stresses decrease monotonously at deformations in the vicinity of the breaking point.

2. The residual stresses can be estimated quantitatively from magnetic-hysteresis loops along and perpendicular to the deformed material that are constructed using adjacent electromagnets.

REFERENCES

1. Ivayanagi, D., Non-destructive method for determination of residual stresses, *Hihakai kensa*, 1974, vol. 23, no. 3, pp. 147–154.
2. Schneider, E., Altpeter, I., and Theiner, W., Nondestructive determination of residual and applied stress by micromagnetic and ultrasonic method, *Nondestr. Meth. Mater. Prof. Determinate Proc.*, 1983–1984, pp. 115–154.
3. Langman, R., The effect of stress on the magnetization of mild steel at moderal field strengths. *IEEE Trans. on Magn*, 1985, vol. 21, no. 4, pp. 1314–1320.
4. Muzhitskii, V.F., Popov, B.E., and Bezlyud'ko, G.Ya, Stress-strain state magnetic control of steel constructions in lifting equipment and high pressure vessels, *Defektoskopiya*, 2001, no. 1, pp. 61–74.
5. Musikhin, S.A., Novikov, V.F., and Borsenko, V.N., Use of coercive force as an indicator parameter in nondestructive measurement of mechanical stresses, *Defektoskopiya*, 1987, no. 9, pp. 57–60.
6. Kostin, V.N., Kadrov, A.V., and Kuskov, A.E., Magnetic properties of a material used to estimate elastic and plastic strains of ferrite—pearlite steels, *Defektoskopiya*, 2005, no. 10, pp. 13–22.
7. Altpeter, I., Dobmann, G., Kröning, M., Rabung, M., and Szielasko, S., Micro-magnetic evaluation of microresidual stresses of the 2nd and 3rd order, *NDT and E International*, 2009, vol. 42, no. 4, pp. 283—290.
8. Bulte, D.P. and Langman, R.A., Origins of the magnetomechanical effect, *J. Magn. Magn. Mat.*, 2002, vol. 251, pp. 229–243.
9. Kuleev, V.G., Tsar'kova, T.P., and Nichipuruk, A.P., The influence of stretching plastic deformations on residual magnetization and initial magnetic permeability of low-carbon steels, *Defektoskopiya*, 2006, no. 4, pp. 61–74.
10. Kuleev, V.G., Evaluation of the relative quantity of residually compressed grains in steels after their plastic extension on the basis of remanent magnetization, *Defektoskopiya*, 2011, no. 7, pp. 12–21.
11. Nichipuruk, A.P., Stashkov, A.N., Kostin, V.N., and Korkh, M.K., Possibilities of magnetic inspection of plastic deformations preceding failures of low-carbon steel constructions, *Deformatsiya*, 2009, no. 9, pp. 31–38.
12. Nichipuruk, A.P., Rozenfel'd, E.V., Ogneva, M.S., Stashkov, A.N., and Korolev, A.V., An experimental method for evaluating the critical fields of moving domain boundaries in plastically tension-deformed low-carbon wires, *Defektoskopiya*, 2014, no. 10, pp. 18–26.
13. Gorkunov, E.S., Povolotskaya, A.M., Solov'ev, K.E., and Zadvorkin, S.M., Effect of plastic deformation and its localization zones on magnetic characteristics of steel 45, *Defektoskopiya*, 2009, no. 8, pp. 3–9.
14. Abuku, S., Magnetic studies of residual stress in iron and steel induced by uniaxial deformation, *Jpn. J. Appl. Phys*, 1977, vol. 16, no. 7, pp. 1161–1170.
15. Kuleev, V.G. and Gorkunov, E.S., Mechanisms of the influence of internal and external stresses on the coercive force of ferromagnetic steels, *Defektoskopiya*, 1997, no. 11, pp. 3–18.

Translated by D. Yakusheva