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Magnetic behaviour of low-carbon steel in parallel and perpendicular directions to tensile deformation

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Abstract

Degradation of a low-carbon steel with plastic tension has been investigated after unloading by magnetic methods (hysteresis and Barkhausen noise (BN) emission). The measurements were done with magnetization in parallel as well as in perpendicular direction to the previous elongation. The dislocation structure formation was checked by transmission electron microscopy (TEM). Evolution of magnetic parameters with applied strain was examined and applicability of magnetic methods for non-destructive testing (NDT) is discussed. It was concluded that the change of the two-peak profile of BN envelope and differential permeability (leading to hysteresis loop bulging) in the parallel direction to the one-peak profile in the perpendicular direction is due to the deformation-driven accumulation of residual stresses.

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1. Introduction

The issue of influence of applied mechanical stresses on magnetic behaviour of ferromagnetic construction materials was one of the first phenomena attracting the scientists' attentions with opening the magnetic era, more than 150 years ago [1,2]. Despite of this, with recent improvement of measurement techniques the seemingly well-investigated topic stimulates lively debates about some interesting magnetic features of stressed ferromagnetic materials: two-peak form of differential permeability [3,4] and Barkhausen noise (BN) envelope [5,6] as well as corresponding bulging of hysteresis loops [4,7,8] with near one-point crossing [2,5,8]. The problem is complicated by a wide variety of chemical and structural composition of investigated commercial steels. The magnetic response can depend fundamentally on such structure details (e.g. presence of two peaks of permeability curve [3] or initial increase of BN energy with strain [5,9,10]). This complex behaviour of magnetic parameters is usually explained by generation of a dislocation structure and residual stresses, which change the domain wall pinning and the magneto-elastic energy, respectively. The existence of inclusions or different structure phases (perlite, cementite, etc.) makes the situation even more confused [4,5].

Aside the physical interest, the problem is very topical for industrial application. There are strong needs for non-destructive testing (NDT) of the structural changes of steels during production processes: rolling, extrusion, cutting or punching. Gas pipeline industry and other steel producers are also interested in the reliable estimation of the remaining life of industrial plants [4,9].

In this work, the complex magnetic investigation (hysteresis loops and BN measurements) of a low-carbon steel after unloading from tension is presented. The magnetizing field is applied in the parallel and the perpendicular directions to the deformation. The characteristic features of the considered problem (one or two peak magnetization processes and cross-points of the hysteresis

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loops) are mentioned. Even though one-peak as well as two-peak profiles of BN envelope and differential permeability are well-known, the change of the profile with the direction of the magnetizing field to the deformation is not well investigated. This change will be explained in the discussion as a consequence of the accumulation of compressive residual stresses after unloading from the tension.

2. Experiment

Commercial low-carbon steel with composition (C = 0.03, Mn = 0.19, Si = 0.13, P = 0.027, S = 0.027, N = 0.007 wt%), grain size of about 50 μm [11], and very small dislocation density in undeformed state was chosen for the investigation. Two series of different samples were prepared: rings (Fig. 1(a)), cut from the rods perpendicularly to the strain direction, and window-shaped samples (Fig. 1(b)). The samples were stretched in an Instron testing machine with constant rate of strain and measured after unloading out of the Instron. The holes in the samples were cut by a water beam, which has a considerably smaller influence on the magnetic properties of the samples than mechanical cutting. The magnetizing and pick-up coils were wound directly on their bodies, uniformly along the whole circumference.

The measurements of the rings and of the window-shaped samples were performed with the measuring system shown in Fig. 2. The personal computer (PC) controls the whole measurement process, involving the feeding Generator Unit with triangular waveform signal and reading the measured data from Data Acquisition Unit. The field strength for the both sample series was calculated from the measured triangular magnetizing current flowing through the magnetizing winding and the effective magnetic path length. Preliminary investigation of the rings was already published in Ref. [12], and will be shown here for comparison with the measurements of the window-shaped samples in the tension direction. Thin foils were cut from the other series of plastically deformed strip samples investigated in Ref. [13], made from the same low-carbon steel, to observe the dislocation structure using a transmission electron microscope (TEM). The results of measurements on these strip samples are similar to the results on the window series, therefore they are not shown here.

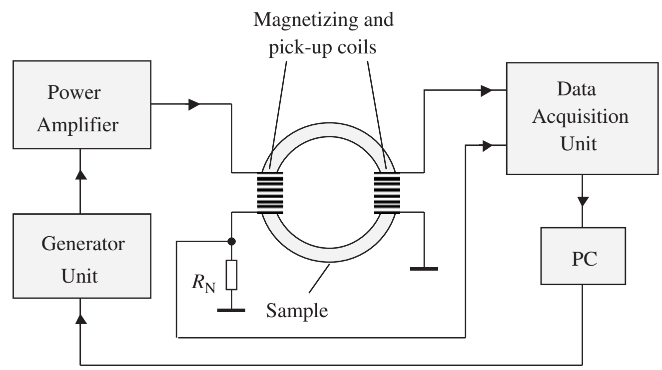

Fig. 2. Sketch of the measuring system.

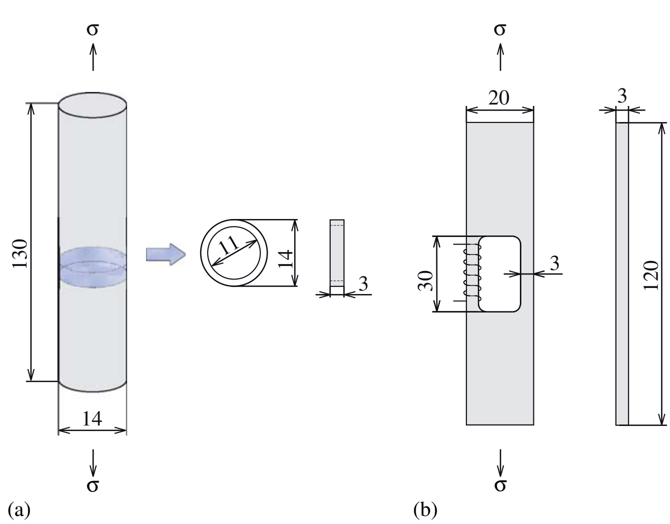

Fig. 1. Ring (a) and window-shaped (b) samples used in measurements with magnetizing field perpendicularly and parallel to the strain, respectively (dimensions in mm for the non-deformed samples are shown).

2.1. Dislocation structure observation

Fig. 3 shows TEM micrographs after various amounts of the plastic deformation. From the micrographs we can see that the undeformed sample (Fig. 3(a)) contains only a small number of dislocations and that the dislocation density increases with the deformation. In the sample strained to 2.3% (Fig. 3(b)), the dislocation structure is represented mainly by isolated dislocations. At the higher strains, the heterogeneous structure with the dislocation tangles (Fig. 3(c)) starts to form, consecutively transforming to the cells (Fig. 3(d)).

2.2. Hysteresis measurements

Differential permeability curves and hysteresis loops for the two considered series of the samples are shown in Figs. 4 and 5. One of the window samples was additionally measured during the tension directly in the Instron ("T" line in Fig. 5(a)) as well as after unloading. The ring and the window samples were measured with a near quasistatic speed $dH/dt = 1.2$ and 1.5 kA/m/s, respectively, and the same field amplitude $H_m = 4$ kA/m. The window samples magnetized along the stress direction show two-peak permeability curves and the corresponding bulging of the hysteresis loops after unloading from the tension. The hysteresis loops for the both series of the stressed samples seem to intersect at certain points in the second and fourth hysteresis quadrants (see the insets in Figs. 4(b) and 5(b)). It is also valid for minor loops (not only for the presented near-saturated ones), but the cross-points move with increase of the field amplitude [8].