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COMPARATIVE STUDY WITH MAGNETIC TECHNIQUES OF P91 AND 13HMF STEELS PROPERTIES SUBJECTED TO FATIGUE TESTS

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We report results of laboratory magnetic inspection of steel properties as a function of a number of fatigue test cycles. The following three magnetic properties have been tested: hysteresis loops of magnetic flux density, Barkhausen noise (BN) signal and magnetoacoustic emission (MAE) signal. Samples of ferritic/bainitic 13HMF and martensite like - P91 type steels had been loaded by MTS machine applying alternative stress with amplitudes of 230 MPa for 13HMF steel and of 350 MPa for P91 steel, respectively. Magnetic properties of both steels vary as a function of a number of fatigue cycles in quite a similar way (relative change of the order of 10%) but evidently the types of those dependencies are different. Those results are discussed qualitatively.

Keywords: Barkhausen noise, magnetoacoustic emission, fatigue tests, P91 steel, 13HMF steel

1 INTRODUCTION

We report results of laboratory magnetic inspection of steel properties as a function of number of fatigue test cycles. This is a part of the research program on elaboration of magnetic non-destructive technique of steel damage detection [1]. The evaluation of residual life of materials loaded cyclically is of great practical importance. This task requires non-destructive tools that would enable one to assess changes in the material state since the beginning of service. Generally, material life during fatigue loading includes successive stages: (i) microstructure changes and accumulation of crystalline defects due to the irreversibility of cyclic deformation mechanisms; (ii) microcrack nucleation and growth; (iii) development of a critical crack (resulting from the fast growth of one crack or from coalescence of several microcracks) leading to rupture. For iron and steel, magnetic properties are correlated in various ways to the crystalline microstructure and hence they can be used to characterize microstructural changes arising in stage (i). Among the numerous magnetic methods previously investigated for assessing changes in the state of ferromagnetic materials after fatigue tests, the Barkhausen noise (BN) technique appeared to be quite suitable [2-4]. However, the results do not seem to be consistent – they reveal different properties of the BN intensity as a function of the number of cycles. It means that more fundamental research is necessary for at least qualitative explanation of impact of fatigue damage on magnetic properties of steel, mainly when this dependence is proposed for nondestructive test application. We argue that fatigue damage state assessment can be more reliable when at least two complementary techniques are used: one based on the BN and second based on the magnetoacoustic emission (MAE). Laboratory test have been performed on two typical steels, exploited in power plant boilers: ferritic grade 13HMF and martensite grade P91. They have been chosen because of intrinsic differences at their microstructure, mainly grain diameter and dislocation density.

EXPERIMENTAL

There have been tested two steels, presently used in Polish power plant industry: ferritic/bainitic – 13HMF grade and martensite like – P91grade. Samples had been subjected to fatigue damage by MTS machine in laboratory of Polish Academy of Science in Warsaw applying alternative stress with amplitudes of 230 MPa for 13HMF steel and 350 MPa for P91 steel, respectively. Magnetic properties have then been tested for two series of samples removed from fatigue machine after a given number of fatigue cycles. Magnetizing setup is shown in Fig. 1.

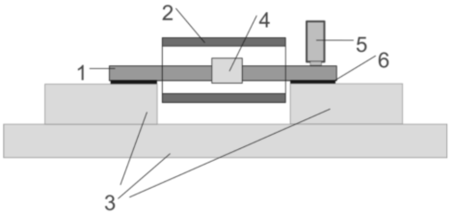

Fig. 1. Magnetising setup. 1 – sample, 2 – solenoid, 3 – C-core yoke, 4 – search coil, 5 – acoustic emission transducer, 6 – attenuating spacer

The sample (1) is magnetized by the solenoid (2) powered by current generator. Delivered current intensity is proportional to driving voltage signal U_g and varies in triangular form with constant time rate. A C-core (3) made of magnetically soft alloy (FeSi) is used in order to close the magnetic flux path. The search coil (4) is wounded on the sample and voltage U_o induced in this coil is used for evaluation of hysteresis loops of magnetic flux density B (low frequency component) and for the Barkhausen noise (BN) measurements (high frequency component), respectively. The magnetoacoustic emission (MAE) is detected with the WD type (made by PAC company) piezoelectric transducer (5). In order to ensure that no acoustic signal originating from the C-core is detected during the measurements, also sound attenuating spacers (6) are applied. Voltage signal U_o induced in the

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searching coil (4) is amplified by a DC preamplifier and recorded with the help of 12-bit analog/digital card for further calculation of $B(U_g)$ loop. High frequency component of the U_o voltage - the Barkhausen noise (BN) - is obtained using analog high pass filter with additional AC amplifier. This voltage is also recorded and its intensity is calculated as rms value (voltage U_b) using LabView based software. The U_b voltage as BN intensity envelope is presented here as a function of the U_g voltage, which is proportional to magnetising current intensity. There is also calculated scalar descriptor of the BN intensity – the integral of U_b voltage over half-period of magnetisation. This quantity is labelled as $IntU_b$. Analogous procedures are used for the MAE signal. Signal from the acoustic transducer is amplified up to 120 dB, filtered (by analog high-pass circuit) and recorded with 12-bit analog/digital card. Time dependence of MAE intensity (an envelope) is also calculated by means of rms value – U_a voltage. Integral of this voltage over half-period of magnetisation ($IntU_a$) is used as a scalar descriptor of the MAE signal intensity.

3 RESULTS AND DISCUSSION

It should be stressed that the three quantities (namely: coercivity H_c, BN and MAE intensities) provide complementary information about the activity of domain walls. Especially the MAE signal seems to be very suitable for the detection of change of internal stress resulting in blocking irreversible jumps of non-180° domain walls. We show here how magnetic properties of both steels vary as a function of fatigue cycle number N ([10^3]). Table 1 gives number of cycles for a given sample.

Tab. 1. Numbers of fatigue cycles for all tested samples (×1000).

N	0	10	25	50	100	200	300	400	500
13HMF	x	x	x	x	x	x	x		
P91	x	x	x	x	x	x	x	x	x

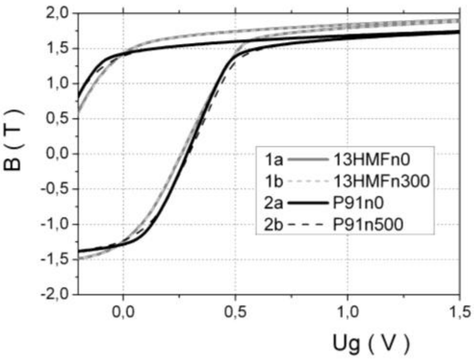

Fig. 2. Zoom of hysteresis loops of magnetic flux density obtained after indicated number (N) of fatigue cycles (×1000) for steel 13HMF (1a, 1b) and P91 (2a, 2b)

The first result concerns hysteresis loops of magnetic flux density. Fig. 2 shows the zoom of these loops plotted for both steels obtained for not damaged state (number of cycles $N = 0$) and after the highest number of fatigue cycles ($N = 300{\times}10^3$ for 13HMF and $N = 500{\times}10^3$ for P91) before rupture, respectively. The differences between these loops shape are evidently very small. P91 steel samples reveal, however, higher level of coercivity than that of 13HMF steel, as expected. This is due to differences in their microstructure. Variation of coercivity (parameter H_c) as a function of number of fatigue cycles N will be presented below, together with the analysis of results of BN and MAE measurements.

Some significant examples of hysteresis loops of the BN intensity (U_b envelopes) obtained for 13HMF steel are shown in Fig. 3. Each plot is a part of hysteresis loop when current intensity varies from negative to positive values (increases). For initial stage ($N = 0$) envelope reveals three peaks.

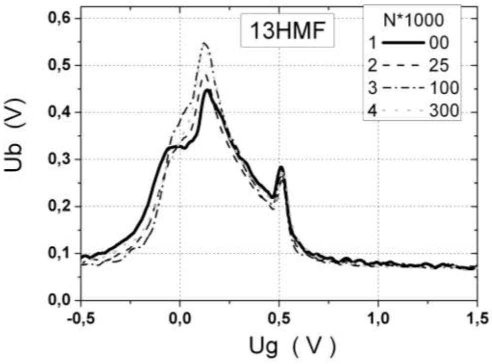

Fig. 3. Envelopes of the Barkhausen signal intensity (increasing field strength) for indicated number N of fatigue cycles(×1000); steel 13HMF

One can find that cyclic fatigue leads to systematic modification of shape of the envelopes: they start to get narrower (due to decrease of the first maximum) and increase of the second peak. The third peak seems to be stable, with a weak tendency to decrease.

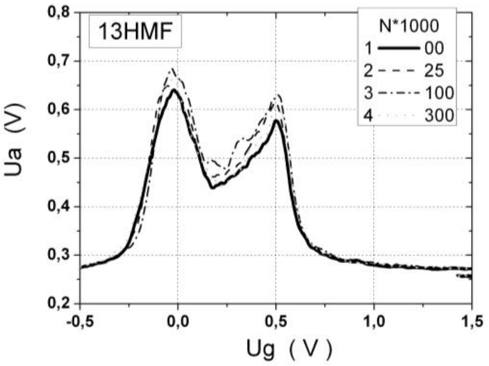

Fig. 4. Envelopes of the magnetoacoustic emission signal intensity (increasing field) for indicated number N of fatigue cycles (×1000); 13HMF steel

Plots of the MAE envelopes for 13HMF steel are presented in Fig. 4 for the same fatigue cycle numbers as for the BN results. These envelopes reveal two broad maxima, attributed to ‘creation’ and ‘annihilation’ of domain walls [6]. Fatigue test modifies heights of both peaks of the MAE intensity as a function of number of fatigue cycles very little and in a non monotonous way. They increase up to $N = 100{\times}10^3$ and than decrease for the greater number of cycles.

Two analogous sets of results are presented for P91 steel in Fig. 5 and in Fig. 6, for the BN and MAE signals, respectively. Envelopes of the BN intensity (Fig. 5) reveal also three peaks in initial stage.

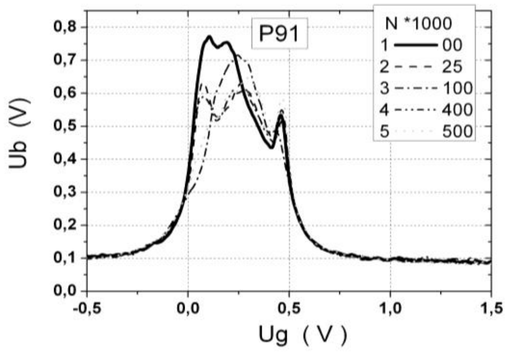

Fig. 5. Envelopes of Barkhausen signal intensity (increasing field strength) for indicated number *N* of fatigue cycles (×1000); steel P91

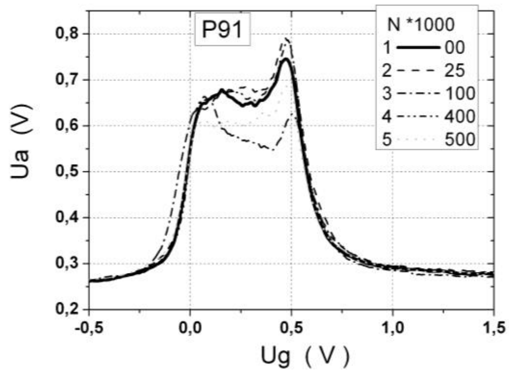

Fig. 6. Envelopes of magnetoacoustic emission intensity (increasing field) for indicated number *N* of fatigue cycles (×1000); steel P91

Their height and position vary with number of fatigue cycles in a rather complex way: first maximum decreases and disappears, second maximum decreases for low number of cycles ($N = 25{\times}10^3$) and than increases while the third - increases. Properties of the MAE intensity envelopes (Fig. 6) evolve also in a complex way as a function of the number of fatigue cycles. The first peak seams to be stable in height up to $N = 400{\times}10^3$ while the second maximum at first increases for low number of cycles (up to $N = 25{\times}10^3$), decreases for higher number of cycles (up to $N = 100{\times}10^3$) and again increases.

More synthetic information about impact of fatigue test on the tested magnetic properties can be assessed when 'scalar' like quantities are introduced. These quantities are chosen as follows: 1 – coercivity (H_c), 2 – integral of the BN intensity envelope ($IntU_b$) and 3 – integral of the MAE intensity envelope ($IntU_a$). All these quantities are related to the not damaged state and plotted in Fig. 7 for 13HMF steel and in Fig. 8 for P91 steel. In the case of both steels there is evident not monotonous variation of all these quantities as a function of the number of fatigue cycles.

Some main properties of these dependencies are summarized in the following statements. The as-observed variations of all tested quantities (relative to initial stage) are quite small – of the order of few % and not monotonous (except for the coercivity of P91 steel). It evidently complicates possibility of detection of damage stage of exploited steel when fatigue damage is the main process of microstructure modification. Addressing the coercivity one can state that its value for 13HMF steel is generally lower than coercivity for initial stage and oscillates (minimum of order of -6% for low number of cycles) while for P91 steel increases monotonously up to +4%. In the case of the BN intensities their modifications for both steels are oscillating in analogous way (with first minimum of order of -7% for 13HMF and -8% for P91) and than maximum with also similar level (about -3%) for both steels. One can find that the BN integral and coercivity H_c vary in a quite similar way for 13HMF steel. However, it is not so in the case of P91 steel. Modifications of the MAE intensity are also different for these steels. Its relative value peaks for 13HMF steel (maximum of order +8%) and oscillates for P91 steel - with first maximum (of order +2%) at low number of cycles and than minimum (of order of -7%) with next broad maximum for high number of cycles). There is also evident 'negative' like behavior of variations of BN and MAE intensities for P91 steel – maxima and minima are reciprocal for both quantities.

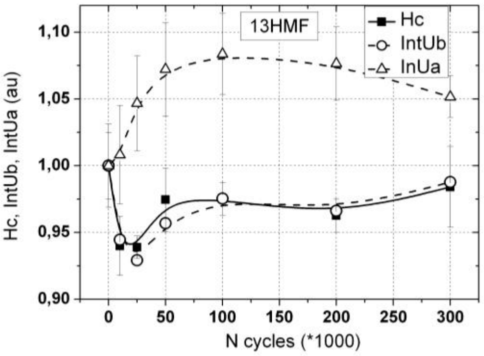

Fig. 7. Evolution of magnetic properties (coercivity H_c, integral of BN intensity, integral of MAE intensity) as a function of number (*N)* of fatigue cycles (×1000); 13HMF steel

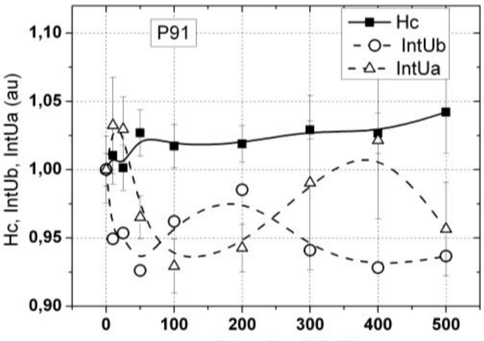

Fig. 8. Evolution of magnetic properties (coercivity *Hc*, integral of BN intensity, integral of MAE intensity) in function of number *N* of fatigue cycles (×1000); steel P91

The - as stated above - non monotonous and different for each steel variations of magnetic properties during fatigue test should be correlated mainly with modification of the density and space distribution of dislocations. It is well known that during the first stage of fatigue an increase in the dislocation density, followed by a reorganization of the dislocation structure, is expected to occur. The last stage of fatigue damage can be also recognized. It typically coincides with the initiation and growth of microcracks that become visible at the surface of the material. The presence of such microcracks is expected to induce two types of phenomena: (i) a rearrangement of the stress field in the specimen; (ii) a local reorganization of the magnetic microstructure. The former (i) is linked with the stress relaxation at the crack surface, reducing the mean stress amplitude near the surface of the specimen and increasing it at greater depth. Without detailed inspection into dislocation structure properties further discussion of our results can be only qualitative and related to the reports of other researchers. There can be, however compared only behaviour of coercivity and BN intensity variation because results of MAE measurements, to our knowledge, are unique.

An increase of coercivity and oscillations of BN intensity for carbon steel are reported in [7] and related only qualitatively to dislocation microstructure modification due to so called low, medium and high level of damage. An increase of BN intensity (of order of +30%) up to 80% of total damage and than decrease and increase just before rupture is reported in [9] and explained (also qualitatively) by initial rearrangement of dislocations and creation of dislocation cells (increase of BN), decrease of dislocation cells dimensions and global increase of dislocation density (decrease of BN intensity) and finally creation of micro-cracks and creation of new closing domains (increase of BN intensity). BN properties modification during fatigue for martensite steel grade P91 was also reported in [8], where results are very similar to ours. First minimum of the BN intensity is explained by a decrease of mean free path of magnetic domain walls due to increase of density of dislocation tangles while an increase of the BN intensity is correlated to creation of dislocation cells. Broad maximum of the BN intensity is explained there by stabilization of dislocation cells microstructure and final increase – by creation of closure domains on micro-cracks. Dislocation arrangement can be also influenced by effect of interaction of dislocations with carbon atoms which are reoriented by moving of domain walls during alternating stressing of steel, as stated in [9].

Modifications of the MAE intensity during fatigue tests are evidently dependent on steel microstructure: its intensity increases and than decreases for ferritic/bainitic steel 13HMF and decreases (with oscillations) for martensite P91 steel. We can state now only qualitatively that it should be related to the specific microstructure of each steel. P91 steel in comparison to 13HMF steel has much smaller grains and much higher initial density of dislocations as well higher level of residual internal stresses (mainly compressive).

4 CONCLUSSIONS

Complementary study by means of magnetic hysteresis loop, Barkahusen effect and magnetoacoustic emission of impact of fatigue damage on ferritic steel (13HMF) and martensite steel (P91) revealed quite different magnetic behavior of these steels. This should be related to differences in mechanical properties of both steels, mainly to density of dislocation and their mobility under applied stress during fatigue tests and also to different residual stress inside the grains. It is known and evident that the influence of dislocations on the magnetic properties during fatigue test is rather complex, leading to either an increase or decrease of the BN and also the MAE intensity. Any rational explanation of all specific features of modification of magnetic properties should be based on detailed information about dislocation rearrangement. At the moment we have no such information.

We would like to conclude, however, that the comparative study made with complementary magnetic techniques such as Barkhausen effect and magnetoacoustic emission give new chance of better assessment of steel properties when fatigue damage is in question. Both techniques can be applied for non-destructive inspection of exploited steel.

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