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SURFACE MAGNETIC NON DESTRUCTIVE EVALUATION USING A PERMEABILITY SENSOR BASED ON THE MDL TECHNIQUE

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In this paper we present a method for non destructive testing of ferromagnetic material surfaces. The method is based on the magnetostrictive delay line (MDL) technique. According to this technique a type of balanced MDL structure is used to determine the magnetic permeability of ferromagnetic surface. The distribution of the measured permeability may be used to determine the plastic deformation of the surface under inspection.

Keywords: magnetic non destructive evaluation, magnetic permeability, magnetostrictive delay lines

1 INTRODUCTION

All currently available non destructive testing and evaluation (NDT) techniques are measuring cracks and defects existing either in the surface or in volume of the material [1]. All these NDT techniques are categorized and rationalized according to their ability of measuring small or large size defects. At this moment there is no industrially applicable technique able to predict the generation of a crack by means of measuring a property, without destruction to the under measurement material.

Concerning metals and particularly steels, the measurement of the local concentration of dislocations defines the steel health or predicts the initiation of a crack on it. Local concentration of dislocations is monotonically related to the stress field distribution in the steel. Dislocations and/or stress field may in general alter the magnetization dependence of the steel under investigation, due to the magnetoelastic energy alteration. Furthermore, dislocations also affect the magnetization reversal by causing pinning of domain wall motion in field amplitudes as small as the magnetization reversal fields.

The important in crack initiation is the local concentration of dislocations and not the average dislocation density. Therefore, bulk magnetization measurement can measure local concentration of dislocations only as local as the magnetization measurement is. On the other hand, surface stresses are related to bulk stress tensor [2]. Hence, measurement of the surface magnetization distribution is the indication of the stress tensor and can theoretically predict the crack initiation. The existing methods for surface magnetization measurement like magneto-optic Kerr effect (MOKE) and Barkhausen noise (BHN) measurements may be used for surface magnetization distribution measurement. But, the difficulties of implementing the MOKE effect and the uncertainties of the BHN method did not allow for industrial application of the methods.

Thus, having the motivation of developing a method for precise and inexpensive surface magnetization distribution measurements, we propose a localized surface permeability measurement based on the magnetostrictive delay line (MDL) technique, according to which surface tests may reveal the prediction of crack initiation on surfaces.

2 THE PRINCIPLE OF OPERATION

The measuring device is based on the arrangement shown in Fig. 1. A balanced set-up of pulsed current excitation conductors is symmetrical around the MDL that is therefore free from any mechanical stresses. Pulsed current I_e is transmitted in the same direction in the two conductors. In the absence of any other magnetic bodies in the neighbourhood of the MDL, the magnetic fluxes from both conductors cancel each other and consequently the absence of pulsed field results in no elastic strain generation; therefore no pulsed voltage output is detected. In the contrary, presence of a ferromagnetic specimen either above or below the balanced conductor – MDL arrangement will affect the magnetic symmetry; this is due to the partial flux leakage caused from the other side conductor. This will generate an elastic micro-strain in the MDL and result in a pulsed voltage output at the search coil. The amount of flux leakage from the MDL to the magnetic specimen and consequently the detected peak voltage V_o depend on the permeability of the ferro-magnetic specimen, the distance between the pulsed-current conductors, as well as the lift-off distance between MDL and the magnetic specimen.

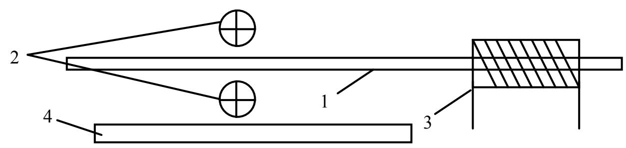

Fig. 1. The MDL balanced structure: (1) − MDL, (2) − Pulsed current conductors, (3) − Search coil, (4) − Magnetic surface under test

Thus, considering the pulsed current – MDL arrangement fixed in terms of relative distances and provided that the distance between MDL and the under

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test material is fixed, the MDL pulsed voltage response depends on the magnetic permeability of the approaching magnetic substance.

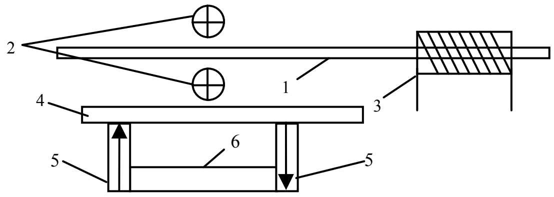

Fig. 2. The MDL balanced structure under permanent magnet biasing field: (1) − MDL, (2) − Pulsed current conductors, (3) − Search coil, (4) − Magnetic surface under test, (5) − Permanent magnets, (6) − Soft magnetic material for magnetic circuit closure

Taking into account that only the surface of the under test magnetic substance contributes to the voltage output change [3], it can be argued that the given MDL arrangement can indirectly determine the surface magnetic permeability of the under test magnetic specimen.

Using the MDL arrangement without any other pre-set magnetic field caused by a permanent magnet or an electromagnet, the detected magnetic permeability or its contribution to the MDL voltage output is due to the remanence permeability or the remanence and the pulsed field permeability of the specimen. This way, arbitrary changes of the magnetic ambient field may result in incorrect measurements. Therefore, it is necessary to fix the amount of ambient field either by means of using a permanent magnet, as shown in Fig. 2 or by using an electromagnet as shown in Fig. 3.

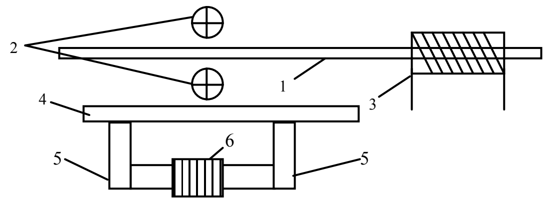

Fig. 3. The MDL balanced structure using electromagnet to generate biasing field: (1) − MDL, (2) − Pulsed current conductors, (3) − Search coil, (4) − Magnetic surface under test, (5,6) − Soft ferromagnets and excitation coil to form the biasing electromagnet

The advantage of using the set-up of Fig. 2 is the low power consumption. The advantage of the set-up of Fig. 3 is the ability of the biasing field modification: this way, the permeability loop (and consequently the magnetization loop just by software integration) of the under test specimen can be determined, provided that the lift off effect is minimized. The permeability loop corresponds to the material close to the pulsed current conductor – MDL intersection. Thus, translating the MDL arrangement on top of the under test surface, the local surface magnetization loops can be determined. The local magnetization loops can then be correlated with the local magnitude of the stress tensor and therefore the local distribution of the local dislocation densities.

3 EXPERIMENTAL AND DISCUSSION

Correlation of the MDL voltage output response and magnetic permeability was initially realized by using a stressed $Fe_{78}Si_7B_{15}$ amorphous magnetoelastic ribbon. Stressing the ribbon with a universal tester its changing permeability was measured by using an electromagnet based hysteresis-graph. The dependence of the MDL voltage output on the magnetic permeability of the amorphous ribbon is illustrated in Fig. 4. The change of the voltage was due to the long range applied stress on the amorphous ribbon. For a minimum distance between MDL and pulsed current conductors equal to 0.1 mm and a minimum lift-off distance between MDL and ferromagnetic specimen equal to 0.2 mm, the obtained maximum MDL output V_0 was around 50 mV. Maintaining this geometry, allows for the estimation of the magnetic permeability at a small area of the magnetic specimen at the MDL-conductors location.

This experiment is actually the proof of concept of the described arrangement, since the residual stresses in polycrystalline steels should offer a similar effect.

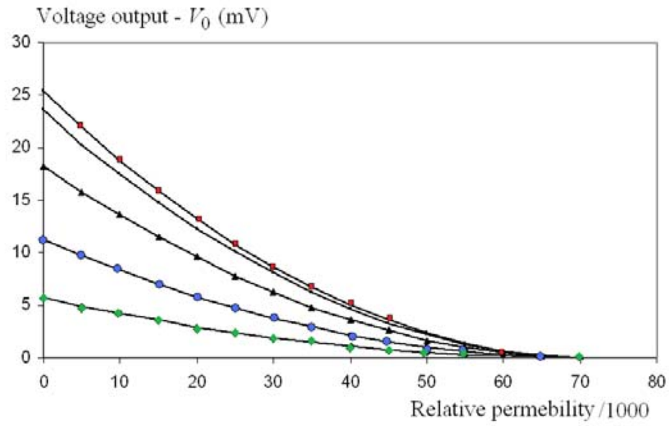

Fig. 4. The MDL pulsed voltage output dependence on the (maximum) magnetic permeability of a stressed amorphous ribbon. Individual curves correspond to different pulsed excitation currents

Armco steel after a mechanical treatment was studied as a representative single phase ferritic steel. The plastic deformation of the dog-bone shaped samples was evaluated by an "Instron" stress machine detecting sample elongation.

Armco bars were also undergone rolling for higher levels of residual stresses. The permeability was determined by a home-made hysteresis-meter in stressed and rolled samples after de-loading, thus measuring the residual stress effect on the samples. A typical response of the hysteresis-meter response is shown in Fig. 5, illustrating the hysteresis-meter induction voltage output dependence on time.

The maximum voltage of Fig. 5 is the indication of the sample maximum permeability. Furthermore, plotting the voltage – time dependence versus the dependence of the applied excitation field on time and consequent integration plot results in the *B-H* loop of the under test sample.

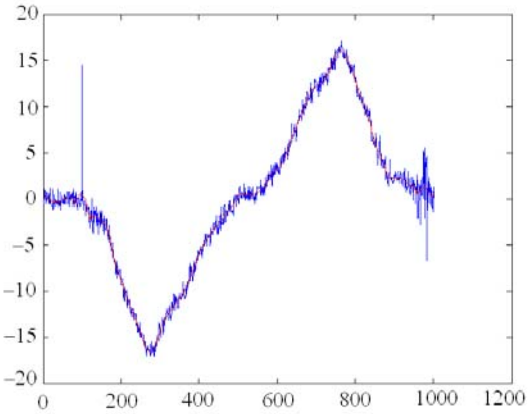

Fig. 5. A typical hysteresis-meter response in mV

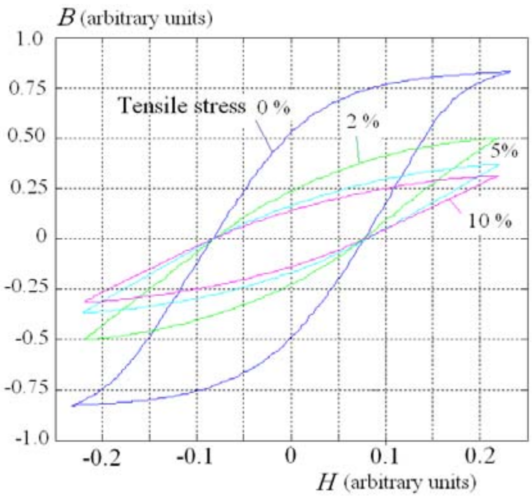

Fig. 6. Typical *B-H* loop of tensile stressed Armco steel after de-loading, illustrating dependence of magnetization on residual stress

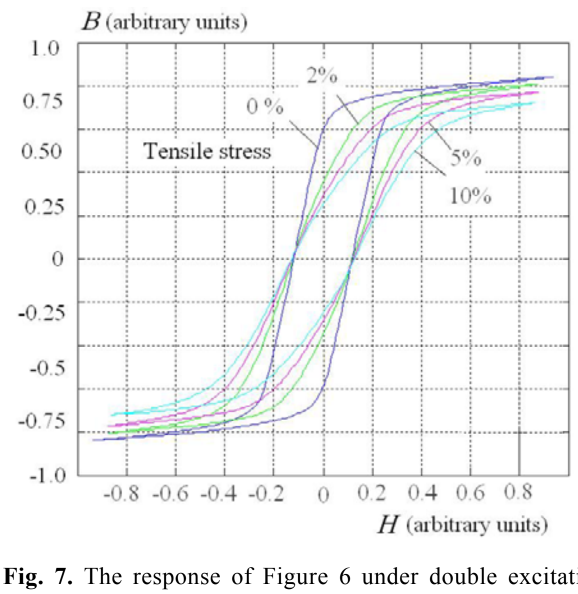

Fig. 7. The response of Figure 6 under double excitation field, illustrating the different loop dependence on residual stresses

Indicative *B-H* loops under different amount of tensile stress and different amount of rolling are illustrated in Figures 6, 7, 8 and 9 respectively.

Magnetic flux density *B* and excitation field *H* are given in arbitrary units as proportional to measured data amplitudes of voltage (mV) and current (A), respectively.

Consequently, the MDL measurements on the stressed samples after de-loading were obtained, in order to determine the residual stress dependence. The MDL pulsed voltage output dependence on the plastic deformation and the magnetic permeability of the tested samples are illustrated in Fig. 10 and Fig. 11 respectively. The response demonstrated an acceptable monotonic dependence of the MDL output V_0 on the plastic deformation or on the material permeability.

Thus, following this type of measurements by scanning the whole under test surface, the uniformity of the

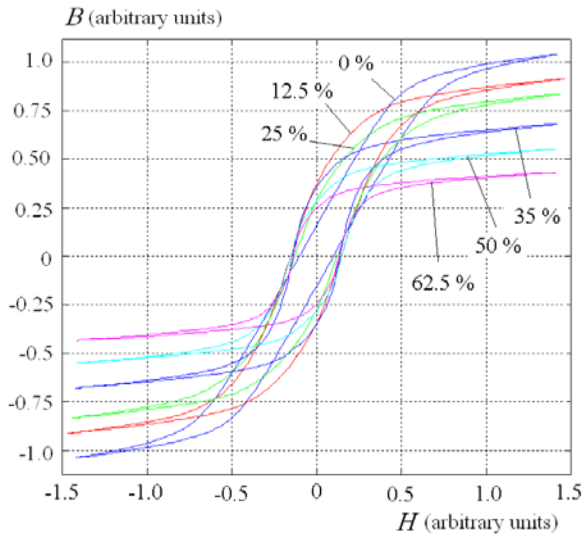

Fig. 8. A typical B-H loop of rolled Armco steel after de-loading, illustrating residual stress dependence on magnetization

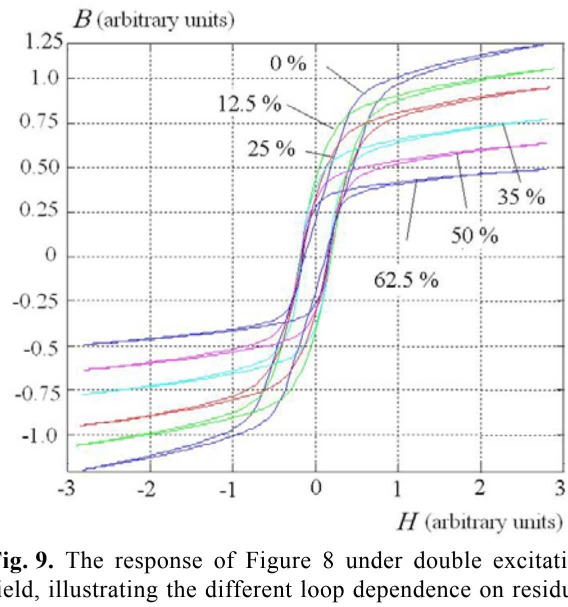

Fig. 9. The response of Figure 8 under double excitation field, illustrating the different loop dependence on residual stresses

magnetic permeability determines the quality of the tested surface. In all measurements the amplitude of the pulsed voltage output V_0 is the system output.

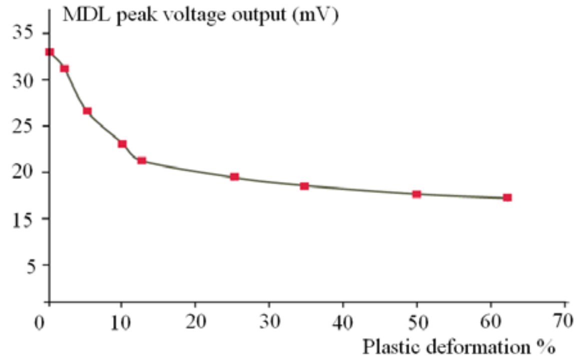

Fig. 10. The MDL pulsed voltage output dependence on the plastic deformation of the tested samples

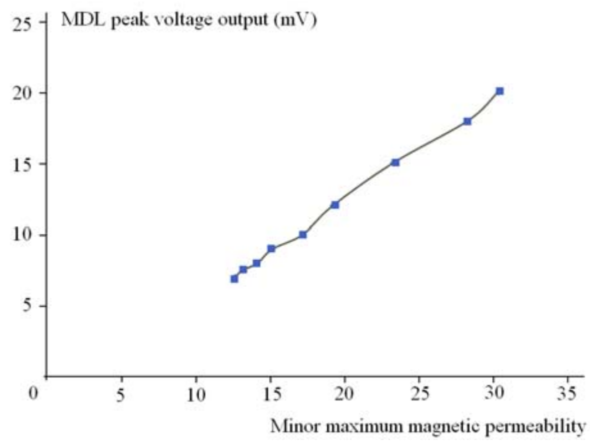

Fig. 11. The MDL pulsed voltage output dependence on the magnetic permeability of the tested samples

Taking into account that the distance between the device and the under test specimen is of critical importance, we performed measurements of voltage output dependence on the distance between device and under test surface, as shown in Fig. 12.

From these results it became apparent that the device response does not change significantly for distances lower than 0.4 mm.

The presented device used for magnetic non-destructive testing has some advantages and disadvantages. Among advantages, the most important is the ability of multiplexing and serializing the information of a number of tested surface regions corresponding to different MDL – pulsed current conductor intersections. The major disadvantage of such multiplexer is the restricted spatial resolution, which is equal to ~80 mm.

The presented method can be used for on-line and off-line measurements. Therefore, the presented device can be used for continuous monitoring of the stress distribution and corrosion on magnetic substances such as pipelines, railways and other ferrous structures.

It is interesting or necessary to investigate the structure and microstructure of the steel under test. The correlation of the microstructure and the magnetic properties may

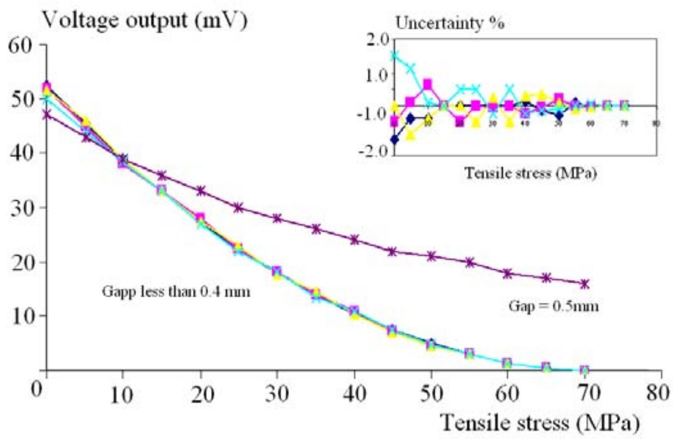

Fig. 12. MDL voltage output dependence on the distance between the device and under test surface

allow for the explanation and simulation of the magnetic response. Structure – magnetization correlation can be obtained by assuming an effective field tensor proportional to the stress tensor

$$[\sigma]=[\mathbf{a}].[\mathbf{H}] \qquad (1)$$

Where [**a**] is correlation matrix, which can be experimentally identified.

This is valid because magnetic anisotropy follows the stress tensor. Stress tensor may be determined by performing stress analysis using high sensitivity XRD measurements. Taking into account that stress analysis results and surface magnetic permeability measurements can determine the sub-surface stress tensor in a surface region of ~ 1 mm^2, it can be concluded that these two methods are suitable for stress-permeability correlation.

4 CONCLUSIONS

The presented balanced MDL device can determine the surface permeability distribution and consequently the magnetization loop of a ferrous substance. Therefore it can determine the dependence the magnetic properties on plastic deformation or residual stresses, as illustrated in this paper. Furthermore, correlation of the stress tensor and magnetization may also offer a precise modeling of magnetization and residual stresses, provided that a precise stress analysis can be performed.

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