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Preliminary Study of the Effect of Remanence on Changes of the Residual Magnetic Field during Tension

Abstract: The development of the application of the residual magnetic field (RMF) (measured on the surface of the ferromagnetic object) as a diagnostic signal involved the analysis of the effect of initial remanence on changes of the RMF during tension. Test plate specimens made of steel P91 (X10CrMoVNb9-1) in various as-delivered states were subjected to increasing active tensile stress. The test results revealed the significant effect of the condition of microstructure and initial remanence on the process and the final values of the RMF

Keywords: residual magnetic field, remanence, active stress

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Introduction

The intensity of the residual magnetic field (RFM) measured on the surface of ferromagnetic elements is used as a diagnostic signal in the magnetic metal memory (MMM) method. The development of the MMM method was initiated at the turn of the 1990s [1–2]. The very notion of the MMM was introduced in 1994 by A. A. Dubov [3]. Presently, the MMM method is used in non-destructive tests and in the diagnostics of technical condition, primarily in Russia, where many related standards have been developed. The method has also found commercial applications in China, Poland, Hungary and, sporadically, some countries of South America. Principal doubts related to the application of the MMM method result from the lack of both quantitative and, in some case also qualitative, assessment-related criteria.

The significant majority of research works concerned with the MMM is focused on the qualitative assessment of the effect of (usually uniaxial) stress on the RFM. The foregoing indicates that the aforesaid tests are basic and, at the same time, demonstrates the necessity of clarifying many issues related to the MMM method and the use of the RFM as a diagnostic signal.

This study involved the attempted analysis of the effect of the initial magnetisation state (remanence) on changes of the RMF during tension. This issue has been nearly absent in scientific publications; the authors have only found three works concerning this problem [4–6]. The above-named works include the comparison of computational results obtained using the magnetomechanic Jiles-Atherton-Sablik model and simple measurement experiments.

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Tests

The tests involved the use of plate specimens made of steel P91 (X10CrMoVNb9-1). The geometry of the specimens is presented in Figure 1. The mechanical properties and the chemical composition of the specimens are presented in Table 1. The specimens were subjected to various heat treatment procedures. The specimen-related details and microstructures are presented in Figure 2.

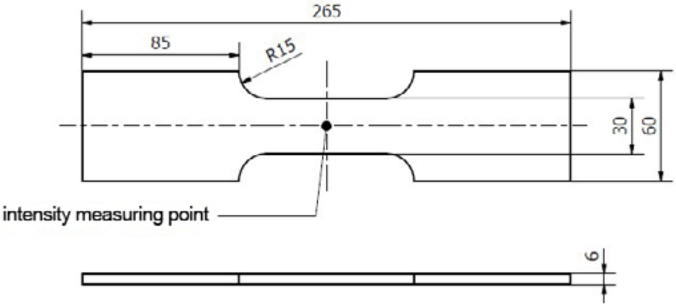

Fig. 1. Geometry of the specimens with the (marked) measurement point

Table 1. Mechanical properties and the chemical composition of steel P91 (X10CrMoVNb9-1)

Mechanical properties														
R_e: > 435 MPa						R_m: 550 – 760 MPa								
Chemical composition (%)														
C	Mn	Si	P	S	Cr	Ni	Mo	V	Nb	Ti	Al	N	Zr	Cu
0.08 – 0.12	0.3 – 0.6	0.2 – 0.5	<0.02	<0.005	8.0 – 9.5	<0.4	0.85 – 1.05	0.18 – 0.25	0.06 – 0.10	<0.01	<0.02	0.03 – 0.07	<0.01	<0.3

The study involved the testing of two states of initial remanence: state A – after the magnetisation of the specimens in the magnetic head (Fig. 3) and state B – magnetisation in the magnetic head (Fig. 3) followed by the demagnetisation performed using a DZC 100 coil (PTS Josef Solnar) (Fig. 4).

The specimens were subjected to active tensile stresses (using a testing machine) within the range of 0 MPa to 400 MPa. The intensity of the magnetic field was measured using a SpinMeter3D ID three-axis meter (measurement range of ±1000 μT, sensitivity 0.1 μT) designated with serial number 170902 (Micro Magnetics Sensible Solutions). Recorded changes of 3 components (in accordance with Figure 5) were the following:

Hx – tangent to the specimen surface, along the direction of tension;

Hy – tangent to the specimen surface, perpendicular to the direction of tension;

Hz – normal to the specimen surface.

Results and discussion

Three measurements were performed in relation to each specimen and each state of initial remanence. As a result, 18 courses of changes of the RMF components in the function of active tensile stress were obtained. The specimen placed in the clamps of the testing machine became a "fragment" of the magnetic circuit. Because of this, the changes of the RFM components presented in Figures 6 through 11 could also be analysed in respect of the flow of magnetic flux through a specimen having a variable cross-section and various magnetic properties changed by active stresses. The primary magnetic flux flowing into the specimen was affected by magnetic resistance, i.e. the reluctance of the part of the specimen characterised by the greater cross-section and being in direct contact with the clamps of the testing machine. Active tensile stresses (assuming the positive magnetostriction of the material) increased magnetic permeability in the direction of stress effect, which, in turn, reduced reluctance and increased the primary flux flowing into the specimen and, at the same time, changed the flux dissipated around the part of the specimen having the smaller cross-section. The aforesaid changes are characteristic of individual components of the RMF. The changes of the components of the tangent parallel to the direction of tension Hx related to changes of stresses involve the change of its value. In turn,

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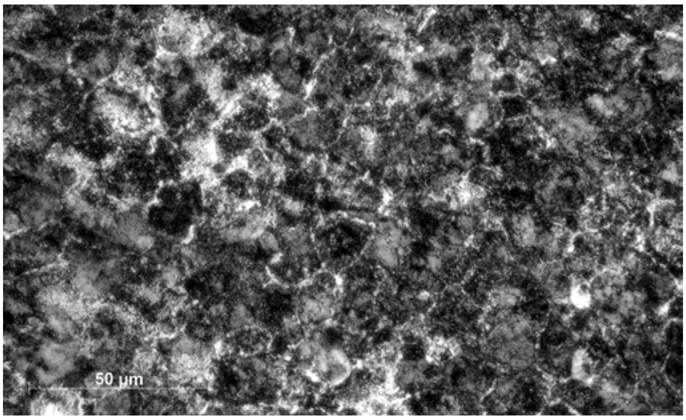
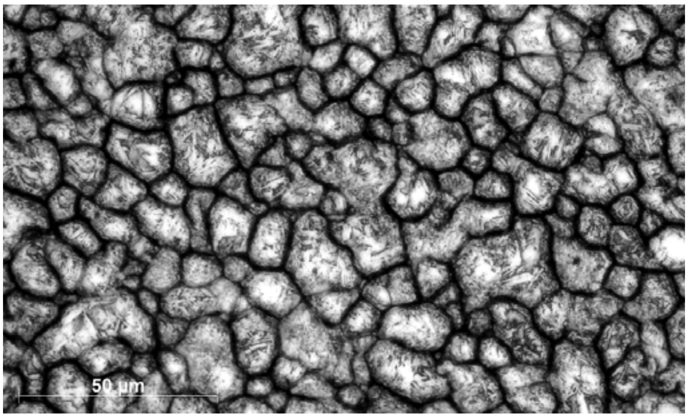
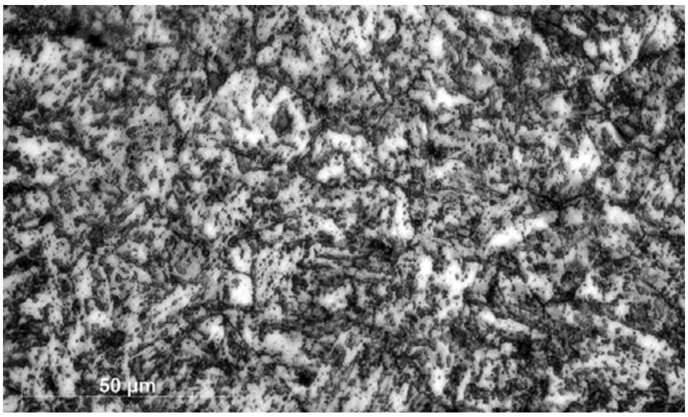


Specimen normalised at a temperature of 1060°C (furnace, air) and, subsequently, cooled in the surface – specimen 1.
Microstructure: fine grains of ferrite with numerous fine coagulated carbides, few fine grains of ferrite without precipitates and areas of ferrite along grain boundaries and around grains.



Specimen after hardening in oil from a temperature of 1060°C (furnace, air) and, subsequently, after tempering at a temperature of 750°C furnace, air) – specimen 2
Microstructure: martensite with a small amount of retained austenite and irregular small areas of ferrite with visible boundaries of primary austenite grains



Specimen in the as-delivered state – specimen 3
Microstructure: high-tempered martensite with numerous fine coagulated carbides and few small irregular areas of ferrite; visible boundaries of primary austenite grains

Fig. 2. Microstructures of the test specimens

Fig. 3. Magnetic head used for the magnetisation of the specimens

Fig. 4. Demagnetising coil DZC 100 (PTS Josef Solnar)

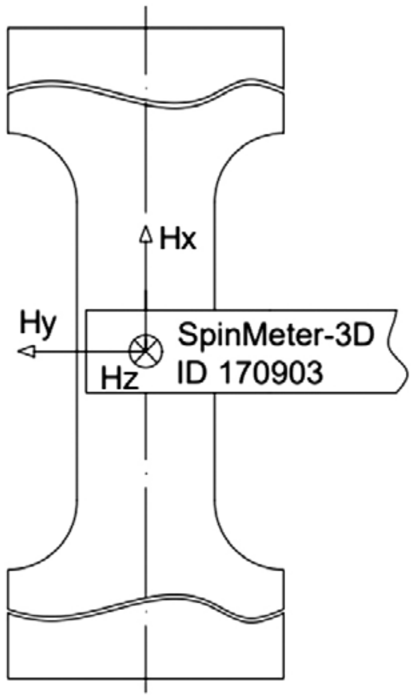


Fig. 5. Position of the meter axis in relation to the specimen

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as regards the component of normal Hz, changes of stresses result in a change of its gradient. This means that, in the area of constant stress, the components of the tangent parallel to the direction of tension Hx, ignoring the effect of geometry and other factors, should have the same value. In turn, the component of normal Hz is characterised by the constant gradient of changes, which results in varying values.

Because the changes of the components of the tangent parallel to the direction of tension Hy and the component of normal Hz were very small (reason: Hy – physics of the phenomenon, Hz – measurement meter located inside the specimen), Figures 6 through 11 present the courses of the component of the tangent parallel to the direction of tension Hx and the value of the module of vector H, where

$$H = \sqrt{H_X^2 + H_Y^2 + H_Z^2} \qquad (1).$$

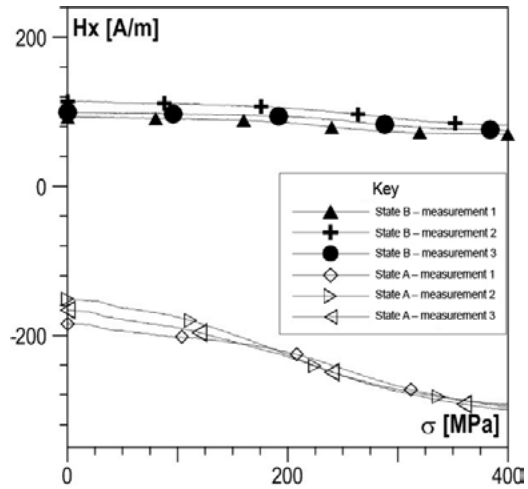

Fig. 6. Specimen 1, component Hx, comparison of states A and B

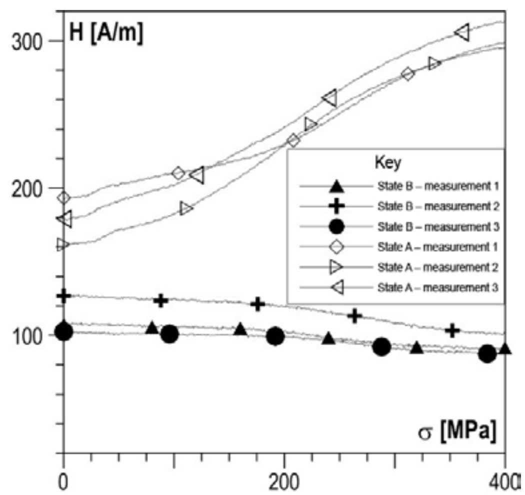

Fig. 7. Specimen 1, comparison of the vectors of the intensity of magnetic field H for the comparison of states A and B

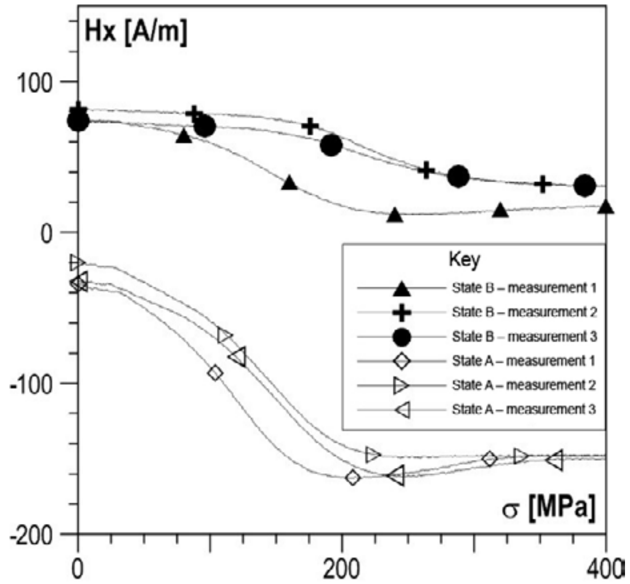

Fig. 8. Specimen 2, axis x, comparison of states A and B

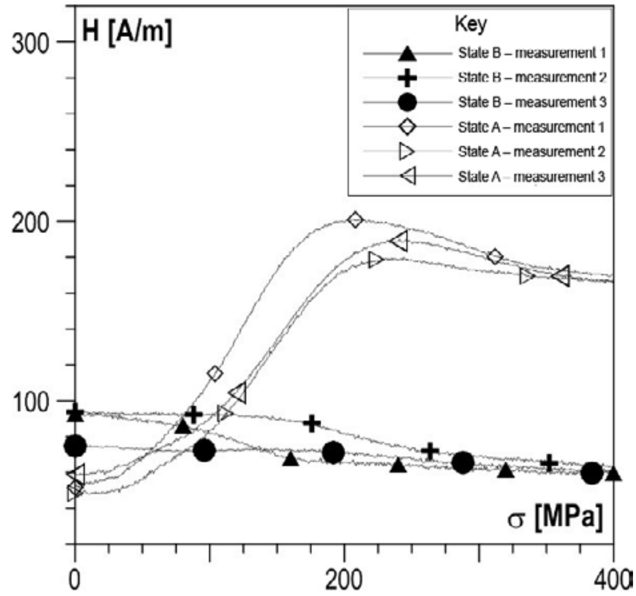

Fig. 9. Specimen 2, comparison of the vectors of the intensity of magnetic field H for the comparison of states A and B

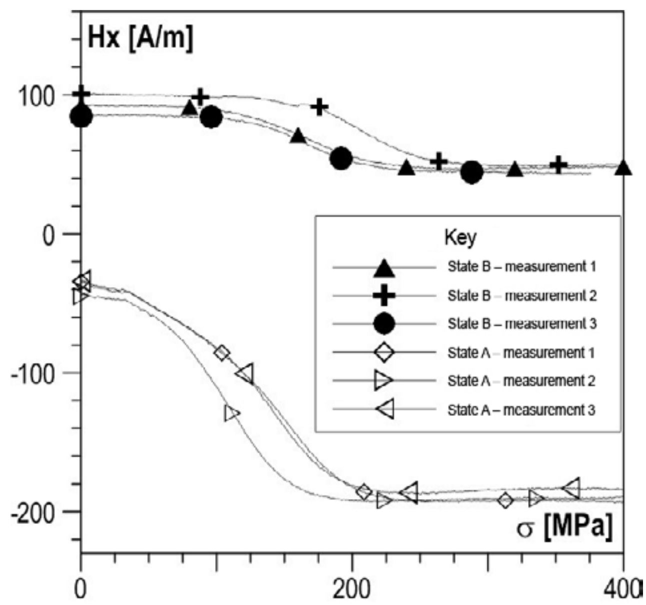

Fig. 10. Specimen 3, axis x, comparison of states A and B

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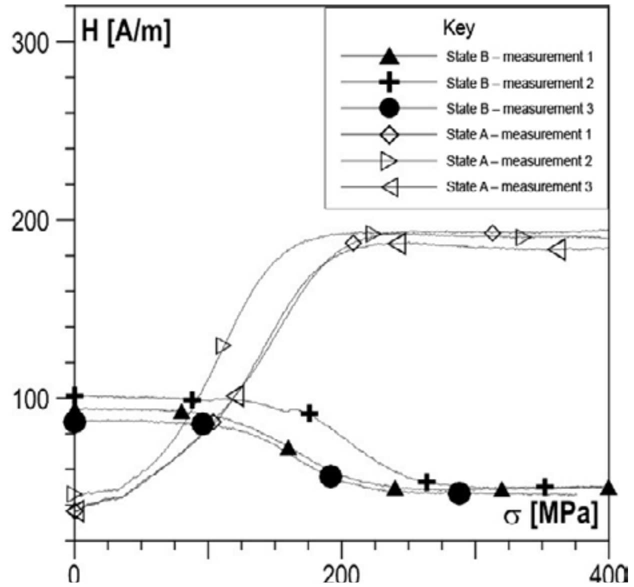

Fig. 11. Specimen 3, comparison of the vectors of the intensity of magnetic field H for the comparison of states A and B

The Jiles-Atherton-Sablik model describing the effect of stress on the process of magnetisation [8 – 11] is based on the assumption that the irreversible change of magnetisation Mirr in relation to the change of the density of elastic energy is proportional to the difference of non-hysteresis magnetisation Ma and irreversible magnetisation Mirr

$$\frac{dM_{irr}}{dW} = \frac{1}{\xi}(M_a - M_{irr}) \qquad (2)$$

where ξ is the material constant (relaxation coefficient).

The energy of elastic strain is expressed by the following formula

$$W = \frac{1}{2}\frac{\sigma^2}{E} \qquad (3),$$

and its differential after being subjected to stress adopts the following form:

$$dW = (\sigma/E)\,d\sigma = \varepsilon\,d\sigma \qquad (4).$$

The model is completed by the following equation:

$$M = M_{irr} + c(M_a - M_{irr}) \qquad (5),$$

where M stands for complete magnetisation and c is the material constant. The first element of the right side of the equation represents irreversible magnetisation Mirr, resulting from the anchoring of domains walls, whereas the second element is the magnetisation component describing the reversible process. By differentiating equation (5)

$$\frac{dM}{dW} = \frac{dM_{irr}}{dW}(1-c) + c\frac{dM_a}{dW} \qquad (6),$$

and entering (2) and (4) the following equation is obtained

$$\frac{dM}{d\sigma} = \frac{\sigma}{E\,\xi}(1-c)(M_a - M_{irr}) + c\frac{dM_a}{d\sigma} \qquad (7).$$

Similarly,

$$\frac{dM_{irr}}{d\sigma} = \frac{\sigma}{E\,\xi}(M_a - M_{irr}) \qquad (8).$$

Non-hysteresis magnetisation is described using the following expression:

$$M_a = M_s\,L\left(\frac{H_e(M)}{a}\right) \qquad (9),$$

where Ms stands for saturation magnetisation, a – constant of effective field scaling, is Langevin function and He represents the effective field determined by the formula

$$H_e = H + \alpha M + \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{d\lambda}{dM}\right)_\sigma (\cos^2\theta - \nu\sin^2\theta) \qquad (10),$$

where α designates the non-dimensional constant of inter-domain coupling, ν – Poisson's ratio, θ stands for the angle between the direction of stress effect σ and the direction of magnetic field H. The third element (added by Sablik et al. [10–12]) represents the effect of stress σ on the effective field (resulting from the magnetoelastic coupling).

The above-presented model and the data by Kuruzar and Cullity related to polycrystalline iron [13] in publications [5–6] were used to present the results of calculations related to the effect of initial remanence in the course

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of magnetisation changes triggered by changes of stresses. The foregoing presents the effect of initial remanence changing within the range of 10 kA/m to 300 kA/m, i.e. the values significantly (by at least two orders of magnitude) higher than those observed in actual conditions. Therefore, it can be stated that, regardless of initial remanence, an increase in elastic strain eventually leads to the course of magnetisation changes in accordance with the curve of non-hysteresis magnetisation. At the initial phase of an increase in active stress, depending on the value of initial remanence in relation to the course of the non-hysteresis magnetisation curve, magnetisation increases or decreases trying to become closer to the curve.

The results presented in Figures 6 through 11 reveal the effect of microstructure on the courses of changes of the residual magnetic field. The courses related to specimen no. 1 (ferritic) differ significantly from the courses related to specimens nos. 2 and 3 (martensitic).

In relation to each of the three specimens, post-magnetisation measurements (state A) reveal the higher effect of stresses on the changes of the residual magnetic field components. The process of demagnetisation (state B) does not significantly affect the initial state of the specimens (particularly as regards specimens nos. 2 and 3), yet it significantly affected the course of the process of changes and obtained final values in relation to a stress of 400 MPa. The above-presented phenomenon is difficult to explain on the basis of currently available subject-related publications. The above-presented model of tensile magnetisation describes the process as similar to non-hysteresis magnetisation. In such a model, an increase in stress should lead to the decay of the effect of the initial magnetisation state.

The results obtained in the measurements were not fully compatible with those obtained using the Jiles-Atherton-Sablik tensile magnetisation model. Reasons for the non-conformity should be search for both in the modelling and in the experiment. Data used in works [5–6] are concerned with polycrystalline iron [13] and not steel P91. In addition, the Jiles-Atherton-Sablik model is not complete yet and still undergoes corrections. In terms of the experiment one cannot exclude the previously described effect of the testing machine-related magnetic circuit and/or overly low active stress in relation to the test steel.

Summary

Recent years concerned with the development of the magnetic method of metal memory has seen the emergence of an issue related to the effect of the initial magnetisation state on changes of the residual magnetic field resulting from active and residual stresses [6–8]. Existing publications known to the authors barely outline the issue, yet, at the same time, emphasize its significance.

The tests of the specimens made of steel P91 in various as-delivered states revealed the effect of the microstructure on the courses of the changes of the residual magnetic field components. The courses related to specimen no. 1 (ferritic) differed significantly from the courses related to specimens nos. 2 and 3 (martensitic).

In relation to each specimen, post-magnetisation measurements revealed the higher effect of stresses on the changes of the residual magnetic field components. The process of demagnetisation did not significantly affect the initial state of the specimens (particularly specimens nos. 2 and 3), yet it significantly affected the course of the process of changes and obtained final values in relation to a stress of 400 MPa.

The above-presented phenomenon is difficult to explain on the basis of currently available subject-related publications. Existing models of tensile magnetisation describe the process as similar to non-hysteresis magnetisation. In the above-named models, an increase in stress should reduce or eliminate the effect of the initial magnetisation state.

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In tests aimed to develop quantitative criteria of assessment in the magnetic method of metal memory it is not possible to ignore the issue of initial remanence and its effect on changes of the residual magnetic field. The foregoing requires both experimentation and the further development of the Jiles-Atherton-Sablik model.

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