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A non-destructive method to determine residual stress in drawn wires based on magnetic measurements

***Abstract**. Estimation of residual stress in drawn wires is an important issue in contemporary metallurgy. The present paper considers the possibility to use a non-destructive method based on magnetic measurements for this purpose. The Jiles-Atherton-Sablik model is used for the description of hysteresis loop.*

Streszczenie.** Oszacowanie poziomu naprężeń szczątkowych w drutach podczas procesu ich wytwarzania jest istotnym zagadnieniem we współczesnej metalurgii. W niniejszej pracy rozważono możliwość wykorzystania do tego celu metody nieniszczącej, opartej na pomiarach magnetycznych. Model Jilesa-Athertona-Sablika wykorzystano do opisu pętli histerezy magnetycznej.* ***Nieniszczące magnetyczne badanie naprężeń w drutach

Keywords: hysteresis loop, residual stress, Jiles-Atherton-Sablik model.
Słowa kluczowe: pętla histerezy magnetycznej, naprężenia szczątkowe, model Jilesa-Athertona-Sablika.

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Introduction

Diagnostics of devices plays an ever increasing role in contemporary industry, as it allows one to eliminate the possible sources of their faults and may lead to substantial economic savings [1-5]. The present paper focuses on a non-destructive method to determine the level of residual stress in drawn wires. Controlling the level of deformation and residual stress during steel-forming processes remains one of the most important problems for metallurgists [6,7]. At present much attention is paid to magnetic methods as useful non-destructive testing and evaluation techniques [8]. The examination of the variation in shape of hysteresis loop for the sample subject to stress may provide information on the stress level [9]. By analogy, hysteresis loop may be an indicator of residual stress level.

The effective field and the Jiles-Atherton model

In order to describe qualitatively how residual stress affects the shape of hysteresis loop, it is expedient to avail of the concept of ,,effective field''. The effective field is the field, which indeed exists within the ferromagnetic sample. It is different from the externally applied magnetic field, as it includes at least one additional term related to the cooperative action between the magnetic moments in the material. The effective field may also include other terms related to some relevant physical phenomena, e.g. stress, viscosity, eddy currents etc. The concept of effective field is extensively used in a number of hysteresis models, but the generic macroscopic example is the formalism developed by Jiles and Atherton [10,11].

The Jiles-Atherton (JA) model is based on the assumption that the process responsible for formation of hysteresis loop is the irreversible translation of domain walls through the imperfections of crystalline lattice, inclusions etc. Jiles and Atherton have proposed a set of equations including an ordinary differential equation and some supplementary relationships to describe the branches of hysteresis loop. In the existing literature there exist a number of different formulations of the JA model equations. The model equations have evolved in time and some researchers have modified them to improve the model capabilities to describe more accurately e.g. minor hysteresis loops [12-16] or to take into account the effects of texture and anisotropy [16, 17] and temperature [18, 19] on the modelled curves. The problems with the apparently simple description and its numerical implementation have been noticed [20-22] and a number of sophisticated procedures for model identification have been devised [12, 16, 23-27].

In the present paper we have decided to focus on a simplified version of model equations, as presented in Ref. [10]. In that version there is no decomposition of total magnetization into the irreversible and reversible components and the rate-dependent effects are considered negligible. The JA model is applied to major loops only and the sole mechanism responsible for a change of loop shape under the applied stress is due to the modification of the relationship for the effective field in accordance with the Sablik's model extension. Sablik et al. [28, 29] have suggested the possibility to extend the JA theory to take into account the effect of stress by the introduction of an additional term in the definition of the effective field

$$H_{\sigma} = \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{d\lambda}{dM}\right) \quad (1)$$

where σ denotes the stress, λ is the magnetostriction, whereas μ_0 is the free space permeability. The full set of model equations and the derivation of the formula for differential susceptibility are given in the Appendix.

The study of interactions of stress with magnetostriction has been the subject of intensive research worldwide [30, 31]. The present paper focuses on the possibility to estimate the level of residual stress in real-life metallurgical products (drawn wires made of high carbon steel) on the basis of measurements of their hysteresis loops.

Experiment

Major hysteresis loops for wires drawn at selected drawing speeds and in the annealed state have been determined with the use of a vibrating sample magnetometer VSM 7301 from Lakeshore. The chemical composition in weight% of the steel C78DP used for production of the wires is given in Table 1. Before drawing the wires had been patented, itched and phospored. The drawing process of 5.5 mm wires down to the final diameter 1.7 mm was carried out in industrial conditions in 12 passes using a modern multi-step drawing machine Koch KGT 25/12. The value of speed in subsequent part of the text denotes the speed at the final drawing die. The sodium-based compound TRAXIT C4540 was used as the lubricant during the drawing process.

Table 1. Chemical composition of C78DP steel

Fe	C	Mn	Si	P	S	Cr	Ni	Cu	Al	N
98.241	0.790	0.610	0.200	0.010	0.013	0.060	0.020	0.050	0.003	0.003

Modelling

The modelling of hysteresis loops was carried out in the following steps:

1. Data points from the experimental major loop for the annealed sample (considered stress-free) were used for creating the reference vector. The vector consisted of 201 equidistant points covering a wide range of field strengths including deep saturation region. The aim of the estimation procedure was to minimize the squared sum of errors between modelled values of magnetization and their reference counterparts (the fitness function value).

The bounds for the JA parameters have been determined. The robust ,,branch-and-bound" algorithm [32] has been used for the estimation purposes. The obtained set of model parameters was $[\alpha, a, k, M_s]$ $= [2.9 \cdot 10^{-3}; 5537\ \mathrm{A/m}; 1102.1\ \mathrm{A/m}; 1.647 \cdot 10^6\ \mathrm{A/m}]$.

Figure 1 depicts the changes of fitness function value vs. number of its successive evaluations during the estimation process. The number of iterations was preset to 100. The final fitness function value was $2.4748 \cdot 10^{11}\ (\mathrm{A/m})^2$. Figure 2 depicts the results of modelling major hysteresis loop for the annealed wire. It can be stated that a good agreement of modelled curve with experiment has been obtained.

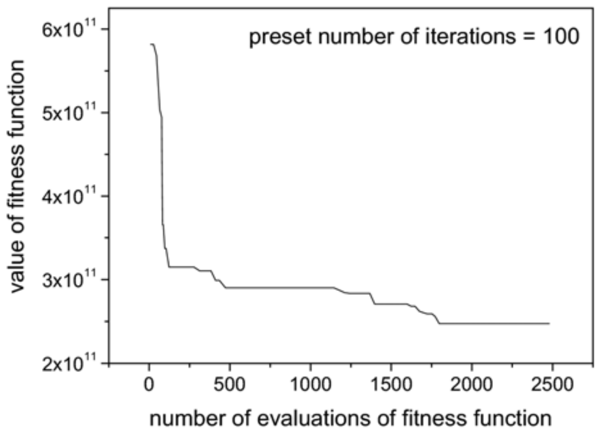

Fig. 1. The changes of the fitness function in the course of the estimation process

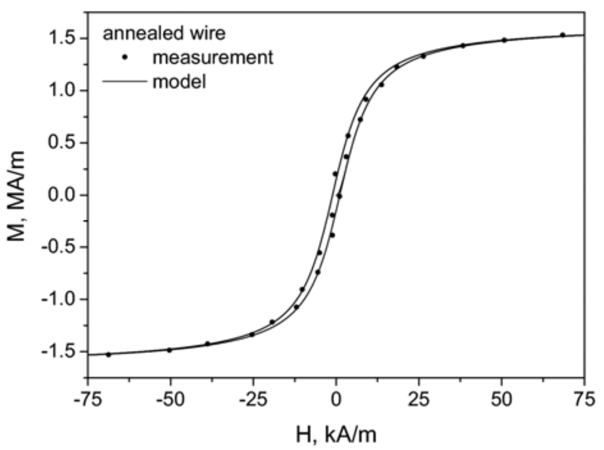

Fig. 2. A comparison of modelled and measured hysteresis curves for the annealed wire.

2. Sablik's formula (1) implies the necessity to modify just one single JA model parameter, namely α - cf. Appendix for details. Therefore the values of remaining parameters should be kept fixed and α is allowed to vary in order to find the optimal values for hysteresis loops of wires drawn at specified speeds. The average value of tensile stress present in the drawn wire are then determined from the difference $\alpha^* - \alpha$, where the asterisk denotes the value of the parameter for the stressed sample.

In the course of preliminary simulations it has turned out that apart from freeing the parameter α, it was expedient to modify the value of another parameter, namely k (this parameter controls the loop width). From Jiles' publications, e. g. [33] it results that parameter k may be identified as equivalent to coercivity. On the other hand, Makar and Tanner [34] have pointed out that coercivity increases with the applied stress and have discussed the effect in terms of underlying physics, focusing on the role of pinning sites. It should be remarked that some authors in their models of magnetomechanical effect based on the JA have modified the values of k, accordingly [35]. Therefore we have decided to increase the values of parameter k as well, in order to match them to the experimentally determined coercivity values.

The determined values of α^* parameter were equal to 0.0083 and 0.01, for v = 10 and 20 m/s, respectively. Therefore the estimated stress levels determined from the dependence $(\alpha^* - \alpha)\mu_0 M_s^2 / 3\lambda_0$ were equal to 307.1 and 403.6 MPa, respectively. In the calculations the value $\lambda_0 = 2 \cdot 10^{-5}$ was assumed following Ref. [28].

Figure 3 depicts exemplary modelling results for two drawing speeds. The modelled curves corresponded quite reasonably to the measured values.

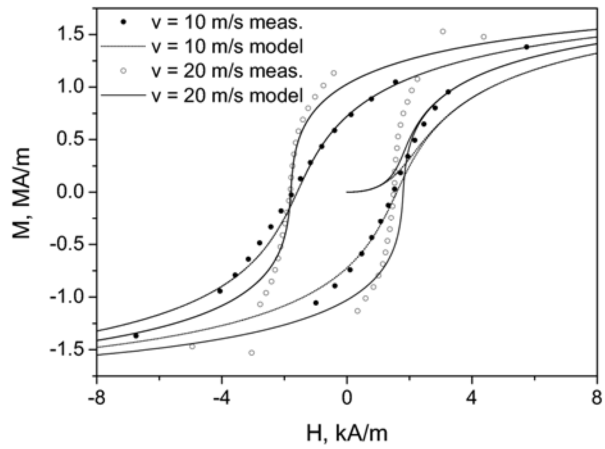

Fig. 3. Measured and modelled hysteresis loops for wires drawn at different speeds.

The obtained values of residual stress in the samples are comparable to the values determined with other means: the Sachs-Linicus (wire polishing) and Schepers-Peiter (longitudinal wire cutting) methods as well as those resulting from FEM simulations [7, 36]. It should be remarked that the presented method determines the average values of residual stress only in the longitudinal direction, however it neglects the residual stress components in the perimeter and radial directions [37].

Conclusions

A simple method of determination residual stress in drawn wires based on magnetic measurements has been proposed. Sablik's concept to modify the ,,effective field" with an additional term of magnetic field strength related to stress has been used in modelling. The average value of residual stress has been determined for wires drawn at two different speeds. It has been shown that residual stress increases with the increased drawing speed; on the other hand it is desirable to carry out the drawing process at enhanced speeds in order to maximize the production output.

It should be remarked that attempts reported in the literature to use the extended Jiles-Atherton-Sablik model in order to determine stress considered specially designed samples and laboratory stands. On the other hand, in the present paper the model is applied to measurement data obtained in the industrial conditions. The presented approach may be a valuable alternative to other approaches as a quick and efficient non-destructive diagnostics tool.

Appendix

The basic set of Jiles-Atherton model equations considered in the paper is as follows:

(A1) $$\frac{\mathrm{d}M}{\mathrm{d}H_{\mathrm{eff}}} = \frac{\delta_{\mathrm{M}}(M_{\mathrm{an}} - M)}{k\delta}$$

(A2) $$M_{\mathrm{an}} = M_{\mathrm{s}}\left[\coth\frac{H_{\mathrm{eff}}}{a} - \frac{a}{H_{\mathrm{eff}}}\right]$$

(A3) $$H_{\mathrm{eff}} = H + \alpha M + H_{\sigma}$$

(A4) $$H_{\sigma} = \frac{3}{2}\frac{\sigma}{\mu_0}\left(\frac{d\lambda}{dM}\right)$$

(A5) $$\lambda(M) \cong \lambda_0\left(\frac{M}{M_{\mathrm{s}}}\right)^2$$

$\alpha, a, k, M_{\mathrm{s}}$ are model parameters, $\delta = \pm 1$ is introduced to distinguish the ascending and the descending loop branches, whereas δ_{M} is defined as $\delta_{\mathrm{M}} = 0.5\left[1 + \mathrm{sign}\left((M_{\mathrm{an}} - M)\cdot \mathrm{d}H/\mathrm{d}t \text{ or } \mathrm{d}B/\mathrm{d}t\right)\right]$.

This pseudo-variable is necessary to avoid the negative $\mathrm{d}M/\mathrm{d}H$ slopes after sudden field reversal, for a detailed discussion cf. [14, 21].

Applying the chain rule for differentiation to Eq. (A1) yields

$$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{\mathrm{d}M}{\mathrm{d}H_{\mathrm{eff}}}\frac{\mathrm{d}H_{\mathrm{eff}}}{\mathrm{d}H} = \frac{M_{\mathrm{an}} - M}{k\delta}\left(1 + \alpha\frac{\mathrm{d}M}{\mathrm{d}H} + \frac{\mathrm{d}H_{\sigma}}{\mathrm{d}M}\cdot\frac{\mathrm{d}M}{\mathrm{d}H}\right),$$

what after re-grouping leads to the expression for total susceptibility in the generic J-A form

$$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{\delta_{\mathrm{M}}(M_{\mathrm{an}} - M)}{k\delta - \alpha^{*}\delta_{\mathrm{M}}(M_{\mathrm{an}} - M)},$$ where the asterisk indicates a modified value of α , increased by the term $3\,\sigma\,\lambda_0/\left(\mu_0 M_{\mathrm{s}}^2\right)$.

In the so-called inverse case, when the flux density $B(t)$ waveform is controlled, the relevant quantity to be calculated at every time instant is $\mathrm{d}M/\mathrm{d}B$; the values of field strength $H(t)$ corresponding to the pairs $B(t)$, $M(t)$ are determined from the transformed constitutive relationship $H(t) = B(t)/\mu_0 - M(t)$ [38]. $\mathrm{d}M/\mathrm{d}B$ may be linked to the above-given expression for $\mathrm{d}M/\mathrm{d}H$ using the relationship

$$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{\mathrm{d}M}{\mathrm{d}B}\cdot\frac{\mathrm{d}B}{\mathrm{d}H} = \frac{\mathrm{d}M}{\mathrm{d}B}\mu_0\left(1 + \frac{\mathrm{d}M}{\mathrm{d}H}\right),$$ thus

$$\frac{\mathrm{d}M}{\mathrm{d}B} = \frac{\frac{\mathrm{d}M}{\mathrm{d}H}}{\mu_0\left(1 + \frac{\mathrm{d}M}{\mathrm{d}H}\right)} = \frac{\delta_{\mathrm{M}}(M_{\mathrm{an}} - M)}{\mu_0\left[k\delta + (1 - \alpha^{*})\delta_{\mathrm{M}}(M_{\mathrm{an}} - M)\right]}$$

It is important to discuss the assumptions for the approximate relationship (A5). Jiles has considered a Taylor series expansion of $\lambda(M)$, leaving just even terms up to 4$^{\mathrm{th}}$ power [39]. According to him, the constant term represents the elastic strain, which does not play any active role in the magnetomechanical effect. On the other hand, it should be remarked that the second term of the aforementioned series expansion is negative for iron-based alloys. Such approach makes it possible to represent the asymmetry of magnetization characteristics for tensile/compressive stresses [40], the effect noticed already in XIX century by Villari [41] and named after him the Villari reversal. Some researchers have confined themselves in their analyses to the quadratic $\lambda(M)$ dependence [28, 42] and neglected in the first approximation the existence of hysteresis phenomenon between λ and M (considered e.g. by Valadkan et al., [43]). The simplification expressed by relationship (A5) results in an effective increase of the value of α parameter for $\sigma > 0$ (tensile stress), what in turn implies a steeper hysteresis loop, as proven by Prigozy [44].

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