ADVANCED METHOD OF THE ELASTOMAGNETIC SENSORS CALIBRATION

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Summary Elastomagnetic method (EM method) is a highly sensitive non-contact evaluation method for measuring tensile and compressive stress in steel. The latest development of measuring devices and EM sensors has shown that the thermomagnetic phenomenon has a strong influence on the accuracy during the EM sensor calibration. To eliminate the influence of this effect a two dimensional regression method is presented.

1. INTRODUCTION

The elastomagnetic (EM) method of stress measurement is a highly precise non-contact method based on the analysis of the magnetic field inside the EM sensor. Stress evaluating devices using the elastomagnetic phenomenon, i.e. the modification of the magnetic hysteresis loop of the ferrous material by static or dynamic mechanical stress, are similar to those, using the effect of change of electrical resistance according to applied stress i.e. resistive strain gauges. The magnetic characteristics of amplitude permeability and incremental permeability in properly chosen working point are, however, about 100 times more stress sensitive than those electrical resistance effects [1, 2]. The relative change of steel's magnetic incremental permeability is up to 10^{-3}MPa^{-1}, while the relative change of a strain gauge electric resistance is about 10^{-5}MPa^{-1}.

2. THEORETICAL BACKGROUND

The main magnetic characteristic of ferromagnetic material is the relation between external (magnetising) magnetic field strength **H** and inner (induced) magnetic field flux density **B**, so called hysteresis loop. Experimentally we can measure the magnetic flux $\phi = \mathbf{A}.\mathbf{B}$ through the cross-section **A**. In practice in any case the measured magnetic flux is combination of a flux, depending on measured magnetic material and a flux depending on sensor arrangement and magnetic surrounding. For precise measurement the magnetic flux must be closed inside the sensor, practically it means magnetic shielding of the sensor.

Amplitude permeability is defined as ratio B/H and incremental permeability is defined as ratio $\Delta B/\Delta H$. In both cases the permeability depends also on "working point" in which it is measured. Only for very high field strength, where no hysteresis occurs (technical saturation), these characteristics are not affected by the magnetic history of material.

Both amplitude and incremental permeability are stress and temperature dependent and they can be used for stress estimation.

3. MEASURING METHOD

The EM sensor takes the form of the hollow cylinder in the middle of which the measured specimen (bar, wire, strand, cable) passes through. The sensing part of the system is the measured specimen itself. The setup consists of primary (magnetising) and secondary (sensing) windings, mounted in a protective steel shield and sealed with an insulating material. The temperature of the material is measured in the middle of the sensing coil by a highly precise temperature sensor tightly connected to the specimen with very low transitional thermal resistance.

As we mentioned before, magnetic permeability is temperature dependent, therefore during the long time measurement the temperature error caused by sensor heating by current flowing through the magnetizing winding may be significant. This drawback was overwhelmed by using pulse method of measuring incremental permeability. The incremental permeability is measured during duration of short and high current pulse so the average energy dissipation is very low and no heating of sensor occurs. Magnetic field inside the sensor is generated by a huge current pulse (peak power value up to 10kW), which magnetizes the specimen to deep saturation (magnetic intensity up to 10^5A/m), simultaneously erasing the magnetic history of the material and hereby creating clearly definable measurement conditions.

By this reason in following we aim our interest on incremental permeability.

4. CALIBRATION PROCESS

The first step of calibration is to measure the incremental permeability μ_{inc} as a function of mechanical stress σ and temperature at various working points H_0. The mechanical stress is measured by precise annular dynamometer. The moment of strain and temperature acquirement is very exactly synchronized in both measurement systems and the acquired data are stored in the control computer with timestamp. From this set of data we choose the working point and fix it for the rest of the calibration process at which the relationship between the stress and permeability is the most linear. At this point the incremental permeability we could represent as

$$\mu(\sigma,T)\Big|_{H=H_0} = \mu(\sigma_0,T_0) + \frac{\partial\mu}{\partial\sigma}\bigg|_{T_0,\sigma_0}(\sigma-\sigma_0) + \\ + \frac{\partial\mu}{\partial T}\bigg|_{T_0,\sigma_0}(T-T_0)$$

For reference values of temperature and stress we should use zero values, hence

$$\mu(\sigma,T) = \mu(0,0) + m\sigma + \alpha T,$$

where $m = \partial\mu/\partial\sigma$, and $\alpha = \partial\mu/\partial T$. The value of $\mu(0,0)$ should be either measured (material without stress at zero temperature) or calculated from the measurements of material without stress at different temperatures.

Our goal is to eliminate the temperature influence due to the thermomechanical effect [3,4]. Typical behavior of the thermomechanical effect is shown in Fig.1. As the measured data show, the temperature change due to applied stress is significant, because the sensitivity of stress measurement is approximately -5MPa^{-1}.

According to this effect it is suitable to divide the regression process into two separate parts. At first the correction of stress values and the consequential correction of temperature values.

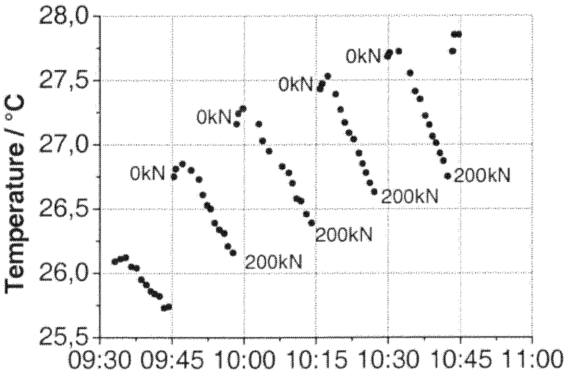

Fig. 1. Typical behavior of the thermomechanical effect.

The two dimensional regression process could be done at once, but with consideration that the proportionality coefficients α and m are also functions of stress and temperature and the functional dependence is unknown, it is appropriate to divide the process into two subparts. Seeking for functional dependencies of each part is more direct and obviously more effective.

Because of the permeability is function of three interdependent variables, we are unable to lock one parameter while the other two are measured. For this reason we are forced to line-up the evaluated points. At first, we should line-up the slightly differing stress measurement point for permeability as a function of temperature. Because of only small deviations, the line-up process would be a small shift along the function $\mu(\sigma,T) = \mu(0,0) + m\sigma + \alpha T$, where the temperature is approximately constant. The coefficient m is calculated as following.

$$\mu(\sigma_1,T) = \mu(0,0) + m\sigma_1 + \alpha T$$
$$\mu(\sigma_1,T) = \mu(0,0) + m\sigma_2 + \alpha T \quad .$$
$$m = \frac{\mu(\sigma_1,T) - \mu(\sigma_2,T)}{\sigma_1 - \sigma_2}$$

By this method we gain a new set of data points of functional dependence of permeability. The next step is to calculate the corrections to the permeability due to temperature influence.

The coefficient α is gained by fitting the permeability as a function of temperature at fixed value of mechanical stress. This fitting is repeated for each value of stress. The new value of permeability for each point now can be calculated as

$$\mu(\sigma,T_{new}) = \mu(\sigma,T_{old}) - \alpha(T_{old} - T_{new}) .$$

By this process we achieve data points that are lined-up both in values of mechanical stress and temperature. We are also able to gain functional dependence between the coefficient α and the mechanical stress σ . Using this functional dependence we are able to predict (interpolate) the function $\mu(\sigma,T)$ for arbitrary value of temperature between two measured functions of permeability.

The calibration curves of the calibrated EM sensor are hence the inverse functions to these gained curves, i.e. the calibration curves are functional dependence of mechanical stress σ as a function of incremental permeability μ .

5. CONCLUSION

The effort to obtain more precise stress measurement device leads to necessity to use more sophisticated methods to gain precise and valuable calibration curves. We use a two dimensional regression method divided to subparts for easy and flexible modification of fitting functions of individual functional dependencies. This regression process is used to eliminate the significant influence of thermomechanical effect on quality and accuracy of calibration curves. The main result of this process is the exact and accurate form of functional dependency of the coefficient α as a function of stress σ , which allow us to calculate the whole net of calibration curves.

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