Universality of the Calibration Curves - the Universality Law

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Abstract. The experimental and theoretical study of the unique magnetic properties of ferromagnetic steels with residual stresses has attracted considerable attention in recent articles. One fundamental aspect of the welding procedure is how the lattice mismatch between the different welding zones induces characteristic changes in the structural and magnetic properties of the ferromagnetic steel. According to our most recent work, the direct manifestation of the intimate relation between the strain state and magnetism stems from magnetostriction through magneto-elastic coupling. We have established the existence of a universal mechanism linking magnetic to mechanical features. The universal (among different steels) character of the effect suggests a novel route towards the non-destructive evaluation of mechanical stresses in welded zones.

Introduction

Ferromagnetic steels have a wide range of applications, such as in nuclear reactors, transformers and automotive gas industries. The efficiency of these structures is strongly related to the distribution of the internal stresses which exist within a material. The residual stresses are responsible for lattice distortions, which lead to a rearrangement of the material’s magnetic domains [1-3].

The total stress vector increases, when an external mechanical field is applied in a ferromagnetic material. This increase affects the microstructural configuration, the magnetic, mechanical and electrical properties of a material. Hence, the knowledge of the existence of the residual stresses in a material should be evaluated, in order to effectively monitor the health of a ferromagnetic steel structure. A significant amount of residual stresses is introduced during the welding process, due to the degradation of the mechanical properties of the welded joints [4-5].

The magnetic non-destructive methods use the combined knowledge of the structural and the magnetic configuration for testing and evaluating metallurgical, microstructure, mechanical properties of ferromagnetic steels grades [6-13]. Many studies have described
the exploitation of several semi- and non-destructive techniques in measuring residual stresses, such as X-ray and neutron diffraction and quasi-dc magnetic permeability measurement [4-5, 14-15]. All these methods can be applied for the stress evaluation of welded materials and can give fast and reliable results.

In this study, a non-destructive method is used for the monitoring of the residual stress distribution in welded steels. This method is based on magnetic permeability measurements. Magnetic stress calibration curves (MASC) have been obtained for three different grades of welded steels. The curves record the dependence of the material’s magnetic permeability on the induced residual stress distribution which is generated through a controlled process of tensile and compressive stresses applied in the elastic deformation region.

The bulk residual stresses were estimated with the neutron diffraction technique, while the spatial surface stress values were determined by the X-ray diffraction (XRD) Bragg-Brentano diffraction technique. The differential magnetic permeability of the examined welded steels is measured by an in-house AC hysteresigraph. The measured differential permeability against the surface or the bulk residual stresses, provide the surface MASC or bulk MASC plots respectively. The MASC curves, are sigmoidal and unique for each steel’s grade and therefore can be used as calibration curves.

The normalized MASC curves are related to both the magnetoeelastic parameters and the stress yield point of the ferromagnetic material. The universal curve, thus obtained, relates the local magnetic permeability to the residual stresses for each ferromagnetic steel grade.

1. Materials and methods

Three representative ferromagnetic steels were studied: a non-oriented electrical steel (NOES), a low carbon steel (AISI 1008) and a micro-alloyed carbon steel (AISI 4130). Two identical sheets of each steel were welded together in a butt joint configuration, with the welding line oriented perpendicular to the rolling direction. The welding parameters were carefully selected in order to ensure full penetration welds, free of defects, such as porosity and cracking. The uniaxial MASC curve of each sample (Fig. 1) is then obtained as follows [4-5, 14-18]. The welded samples are cut according to American Society for Testing and Materials E8 [19] and subjected both to compressive and elastic stresses within the elastic deformation range, at a constant initial strain rate of $10^{-4}\text{ s}^{-1}$, by a loading machine, until given levels of strains, within the elastic region, are achieved. To establish the strain level, a commercially available strain gauge is adhered on the surface of the under test sample, at its centre. According the elasticity equations, the measured strain values were converted to stress values.

![Fig. 1. Bulk calibration curves for different grade of steels.](image-url)
The differential magnetic permeability of the various welding zones of the pre-strained and unloaded samples were measured by an in-house AC hysteresigraph. The examined specimens are placed in the centre of an excitation solenoid. The excitation coil ensures a homogeneous magnetic field at its centre generated by a sinusoidal magnetizing current of 0.1Hz produced by a programmable function generator connected to a power amplifier. The magnetic circuit closes through a U-shaped magnetic laminated core (Fig. 2).

![Fig. 2. Cross-section of the AC hysteresigraph. (1) electromagnet, (2) excitation coil (Cu wire with diameter of 0.5 mm), (3) sensing coil (Cu wire with diameter of 0.2 mm) and (4) examined sample.](image)

The voltage induced at the ends of a sensing coil wound around the sample is proportional to the sample’s differential permeability in the longitudinal direction. This output signal is then amplified and filtered, in order to remove low-frequency interference and high frequency harmonics. The filtered output voltage is recorded by a microprocessor with A/D converters to ensure real time measurements. The procedure is controlled via a MATLAB Graphical User Interface allowing the recording of both the excitation field and frequency, as well as the output pulse. The recorded voltage as a function of the applied field yields the magnetic permeability loops. The hysteresigraph is not calibrated and the input and output values shown are in arbitrary units (a.u.).

The similarities of the three curves in Fig. 1 suggest the existence of an underlying universal curve which scales according to the magnetostrictive and stress-strain characteristic of the material. To illustrate this, residual stress values were normalized against the maximum one for each sample and the measured magnetic permeability values were normalized against the maximum permeability value, observed at the maximum yield point residual stress level, in each case. Indeed, all normalized calibration curves (Fig. 3) collapse into one.
2. Results and discussion

In order to probe further into the question of universality, the normalized stress derivatives of the original calibration curves were computed (Fig. 4) and compared with the magnetic permeability as a function of the applied field used for the permeability measurements (Fig. 5).
Fig. 5. Measured magnetic differential permeability loops for different grades of steels at maximum elastic stress level.

The two sets of curves are similar to each other exhibiting the same trends in location of maxima and profile shapes. This behavior is linked to the magnetomechanical effect, i.e. the effect of magnetostriction on the magnetic as well as on the elastic material properties. At constant temperature T, magnetic induction B as well as deformation λ is a function of both applied field H and stress σ:

\[ B = f(H, \sigma) \]  
\[ \lambda = f(H, \sigma) \]  

Differentiating Eq. (2) arises:

\[ \frac{\partial^2 B}{\partial \sigma \partial H} = \frac{\partial}{\partial \sigma} \frac{\partial B}{\partial H} = \frac{\partial}{\partial \sigma} \mu \]  

where \( \mu \) is the differential permeability (proportional to measured output voltage) at a given stress level \( \sigma \). Thus, the calibration curves are a function of quasistatic measurements of \( \mu_{\text{max}} \) at various stress levels \( \sigma \). Since, the Eq. (4) describes the normalized stress derivative of the calibration curves.

Differentiating Eq. (3) yields:

\[ \frac{\partial^2 \lambda}{\partial \sigma \partial H} = \frac{\partial}{\partial \sigma} \frac{\partial \lambda}{\partial H} \]  

which is the stress derivative of the field derivative of the magnetostriction curve.

The stress derivative of Eq. (2) is \( \frac{\partial B}{\partial \sigma} \) at constant field H and the field derivative of Eq. (3) is \( \frac{\partial \lambda}{\partial \sigma} \) at constant stress σ.

According to le Chatelier equilibrium principle, in the absence of hysteresis, the two derivatives are equal: \( \left( \frac{\partial B}{\partial \sigma} \right)_H = \left( \frac{\partial \lambda}{\partial \sigma} \right)_\sigma \) and for infinitesimal changes of H and σ:

\[ \frac{\partial^2 \lambda}{\partial \sigma \partial H} = \frac{\partial}{\partial \sigma} \frac{\partial \lambda}{\partial H} \]  

(6)
The deformation at zero applied magnetic field is given by the ratio \( \frac{\sigma}{Y} \), where \( Y \) is the material’s Young’s modulus, due to the fact that all the measurements are obtained in the elastic region of the stress-strain curve. Upon the application of field \( H \) along the direction of applied stress, the total deformation \( \lambda \) for a given stress level changes because of magnetostriction:

\[
\lambda(\sigma, H) = \frac{\sigma}{Y} + \lambda_{\sigma_0}(H) \tag{7}
\]

where \( \lambda_{\sigma_0}(H) \) is the (positive or negative) magnetostriction curve at zero stress. At a given residual stress level and assuming operation in the linear region of the anhysteretic magnetostriction curve, the maximum differential permeability, observed during the quasi-static measurement of the \( B(H) \) characteristic, is proportional to the field derivative of the magnetostriction curve \( \lambda(H) \):

\[
\mu(\sigma, H) \propto \frac{\partial \lambda(\sigma, H)}{\partial H}.
\]

Hence, the calibration curves obtained in this work are also a measure of the \( \frac{\partial \lambda}{\partial H} \) characteristic as a function of residual stress and the sign of \( \sigma \) decides the increase or decrease of permeability from the stress free permeability \( \mu_{\sigma_0} \).

3. Conclusions

The innovation of the present study is the normalization of the magnetically calibrated stress curves of steels against their magnetoelastic characteristics and the yield point of each grade of steel. The universality is suggested by the similar phenomenology exhibited by all calibration curves obtained. The above described formalism, which stems from the novel evaluation methodology proposed and has been verified for several grades of steels, suggests a way to link permeability to magnetostriction and permits break-through scientific results with immediate effect in numerous existing industrial applications and the respective industries.

References


