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Using AMR Sensors for Surface Residual Stress Determination in Steel Constructs

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Abstract

In this paper, a non-destructive methodology designed for quantification of residual stresses in magnetic steels is presented. A portable anisotropic magnetoresistance (AMR) sensor has been developed for specimen inspection capable of determining the distribution of magnetic permeability tensor in a contactless manner. Correlating the AMR response with residual stresses, the localized stress tensor has been determined. This method holds significant promise for enhancing the reliability and safety of critical components in various ship-environment applications and beyond.

Keywords: Non-destructive testing, Anisotropic magnetoresistance, Residual stress, Magnetic permeability, Fatigue assessment, Finite element analysis

1 Introduction

Residual stresses and/or strain gradient monitoring is an important parameter to determine and monitor the structural and conditional health of steels and steel structures. Mechanical and thermal fatigue during manufacturing process or during steel operation introduce dislocations, dislogation forests and finally nano-craks and crack in the steel. Beyond the yield point, plastic deformation includes already nano- and micro- cracks that are formed in order to achieve stress relief. These cracks propagate in certain directions leading to possible steel failure. Therefore, it is vital to monitor the evolution of residual stress or strain gradients over time -even in the elastic region-, to observe the tendency to reach the yield point and therefore generate a crack. Additionally, a sharp spatial gradient in residual strains or stresses before yield can result in a crack initiation, while a uniform distribution of higher level of residual stresses may not lead to a fracture [1].

The current industrial methods of non-destructive stress monitoring are the strain gauge [2], as well as the hole drill method [3], both used for local surface monitoring, having several operating limitations. Neither method can provide distribution stress monitoring. Recently, non-linear acoustics have been used for residual stress monitoring, allowing for distribution stress measurements [4].

As steel materials and structures exhibit magnetic properties, magnetic methods have also been proposed and investigated as an alternative or complementary to the above sensing methods [5]. The magnetization process and resulting macroscopic magnetic properties depend on the crystalline structure as well as on the microstructure at the grain level [6]. Residual strains affect the anisotropy profile and residual stresses act as effective magnetostatic fields on the spatial variation of the magnetization. Hence, microstructural changes related to residual stresses may be detected through the monitoring of macroscopic magnetic parameters obtained from hysteresis loop measurements, such as the differential magnetic permeability [7], from magnetic Barkhausen noise (MBN) measurements [8] and from magnetoacoustic waves [9, 10].

The magnetic stress calibration (**MASC**) curve principle has been proposed to quantitatively link residual stresses, determined through X-ray diffraction measurements in the Bragg Brentano arrangement, to the differential permeability or the MBN rms voltage [11]. It has been found that a unique MASC curve can be obtained for each given steel grade: it is of sigmoidal shape with stress along the horizontal axis and the magnetic property on the vertical axis. The MASC curve can be used to convert a measured value of differential permeability to residual stress. Obtaining MASC curves is a laborious process, which is perfomed only once for a given steel grade. However, this process led to the following observation: normalizing the residual stress σ (X-axis) against the yield point of the given steel and of the magnetic permeability μ (Y-axis) against the maximum value of the differential permeability, all MASC curves collapse into one single curve, called the universal MASC curve [11].

In this paper, we introduce the anisotropic magnetoresistance (AMR) measurement in order to determine residual stresses on the surface of magnetic steels. Such sensor has some advantages, namely low power consumption, contactless measurement up to 10 mm far from the surface of the under test steel, and ability of moving along the under test steel to determine gradient effects.

2 Flux leakage without surface crakcs in the presence of residual stresses

The novelty of this study lies in measuring the flux leakage in the absence of cracks, but in the presence of residual stresses, on the surface of magnetic steel specimens. The idealization presented assumes only surface residual stresses, i.e. for depths in the order of 10 – 100 μm, without any loss of the generality. Any residual stresses are expected to result in an increase or decrease of the differential magnetic permeability of the material as follows:

- If the material is positively magnetostrictive[*] at a given direction, then any tensile residual stresses will result in an increase of the differential magnetic permeability and a decrease of the coercivity field Hc[†], while any compressive stresses at a given direction, will result in a decrease of the differential magnetic permeability and an increase of the coercive field Hc.
- If the material is negatively magnetostrictive at a given direction, then any tensile residual stresses will result in a decrease of the differential magnetic permeability and an increase of the coercivity field Hc, while compressive stresses will result in an increase of the differential magnetic permeability and a decrease of the coercive field Hc.

Residual stresses can be assumed to operate like an effective magnetic field which is added or subtracted on the biasing field. If in one axis e.g. the X-axis, the magnetic material is positively magnetostrictive, then

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[*] Magnetostrictive material is defined the magnetic material changing its dimensions under the influence of magnetic field (in the order of part per million – ppm). Positive magnetostrictive material is the magnetic material with increasing dimensions along the applied field, where the opposite occurs for a negative magnetostrictive material.

[†] Coercive field is the biasing field in which the macroscopic magnetization of the magnetic material is null.

it will be negatively magnetostrictive in its perpendicular counterpart e.g. the Y axis. Notwithstanding this, the same principles apply for positive and negative magnetostriction materials concerning bulk residual stresses, i.e. including residual stresses in the Z-axis. All these are valid under the assumption of absence of cracks in the material.

By moving an AMR sensor along the X-axis of a positively magnetostrictive material will result in a decrease of the magnetic flux in the X & Z axes and an increase in the Y-axis, in case of tensile residual stresses. The opposite is expected for compressive stresses. Moving the AMR sensor along the X-axis of a the same (positive magnetostrictive material) under compressive residual stresses will result in an increase of the magnetic flux in the X & Z axes and a decrease in the Y-axis. The opposite is expected for the case of negative magnetostrictive material in each direction. Tensile stress will result in an increase of X & Z field component, as well as in a reduction of Y-axis field component. The opposite holds for compressive stresses. This behavior is illustrated in Fig 4.

In contrast to surface defects which lead to magnetic lines distortion of the order of 100-200μT, the magnetic field distortion due to residual stresses is much smaller, notably in the range of nT to a few μT. The use of AMR sensors because of their sensitivity to the order of nT and their capability to display 3-dimensional field measurements makes them the most suitable option for such measurements.

The problem is the knowledge of the positive or negative magnetostrictive character of an under test steel specimen. However, this is not of paramount importance, since the spatial gradient of the residual stresses is the decisive factor for fatigue failure assessments and for making predictions on the remaining lifetime of a steel. However, the determination of the positive or negative character of magnetostriction can be precisely determined by observing the evolution of the response of an array of AMR sensors over time, using AI-ML algorithms and protocols. This is work in progress.

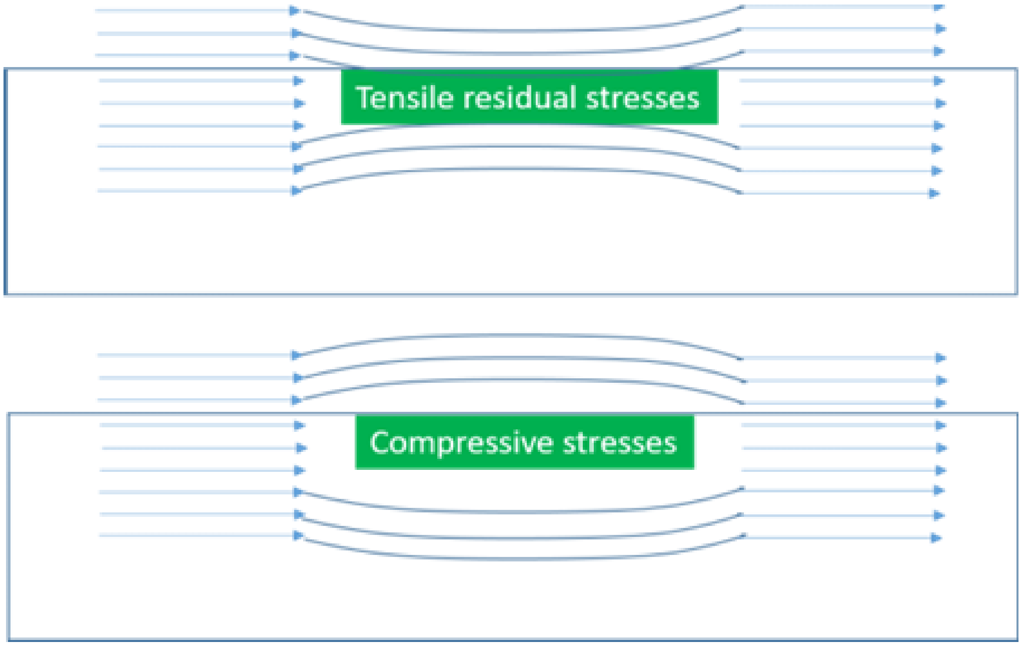

Figure 4: Change of the orientation of magnetic lines in a positive magnetostrictive direction under the influence of tensile and compressive stresses.

An important issue is the correlation of the AMR output (in V or T) with residual stresses (MPa), offering the prediction of location and time a steel failure may happen. Fundamental to this is the spatial and periodic monitoring of the differential magnetic permeability as presented in the following sections.

3 AMR response with and without biasing field

By an electromagnetic yoke it is possible to compare the magnetic flux leakage, as measured by the AMR sensor in the X, Y and Z axis, with the presence or absence of the additional biasing field. Under zero biasing field, the specimen is magnetized by only the Earth's magnetic field. Under the influence of additional biasing field, the flux leakage screens additional information about the status of residual stresses in the steel specimen. Until it is driven to saturation, the magnetic flux leakage will increase or decrease as a function of the residual stresses with respect to the positive or negative character of the magnetostriction in each axis. After exceeding the saturation level, any additional biasing field becomes insignificant within the context of this study. This is because the additional magnetic lines are not trapped by the material. In that case the AMR sensor's response is not dependent on residual stresses, but only on the additional biasing field applied.

Figure 10: Electric steel samples after mild (top) and heavy (bottom) induction heating.

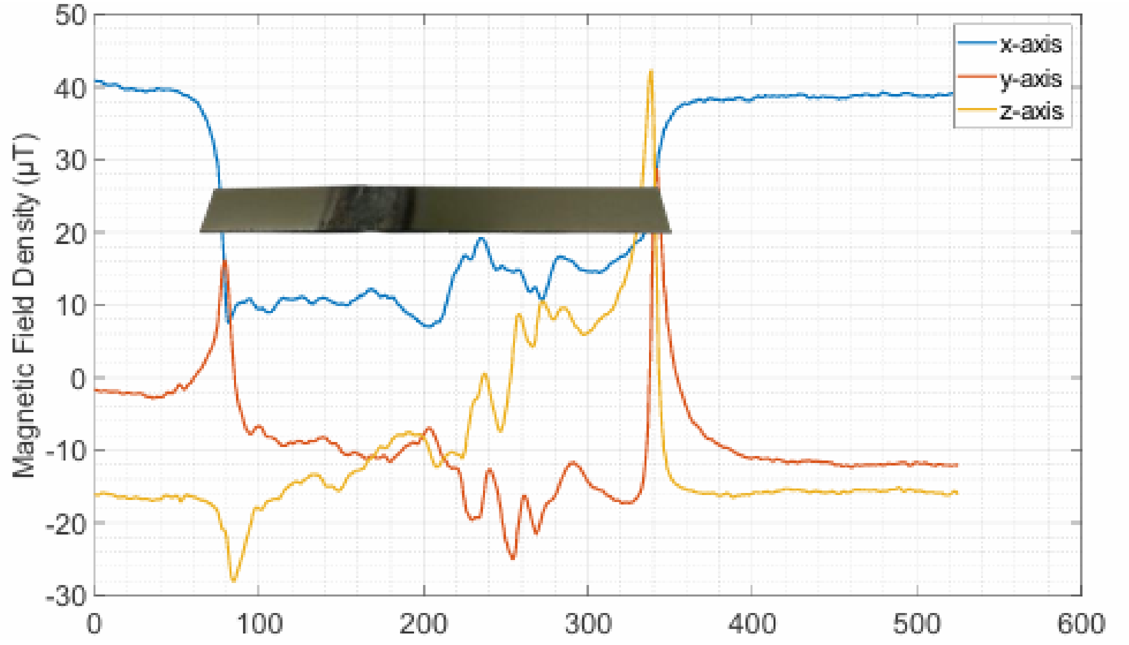

Figure 5: 3D AMR response without the biasing DC magnetic yoke (steel element in physical dimensions with respect to distance measurements).

To qualitatively highlight the differences between the two methods, a specimen in which residual stresses had been intentionally introduced by localized RF heating and consequent quenching was used. The AMR sensor's response, along the path length assumed for the test specimen, without using an additional biasing field, is illustrated in Fig 5. Respectively, the AMR sensor's output along the same path on the same specimen, using a biasing field introduced by a DC magnetic yoke (Fig.1) is illustrated in Fig 6. It is apparent that the sensitivity of the AMR sensor is better in the case of not using a biasing field, as it allows for the identification of several small-scale stress fields along the test path, which in the case of using the biasing field go unnoticed. This happens because magnetic domain walls overpass easily the small residual stress fields in case of elevated biasing field, while Earth's biasing field allows only for small Barkhausen jumps[‡] for small stress fields. Thus, the characterization of the steel in the absence of biasing field, for the case of AMR sensors, is preferable, allowing for a more detailed mapping of stress field.

It is worth noting that the large terminal field changes, at about 100 mm and 350 mm, refer to the boundaries of the steel specimen, allowing for knowing where the steel specimen is, while all the rest of signals inside the envelope of the outer large signals illustrate smaller and larger stress fields.

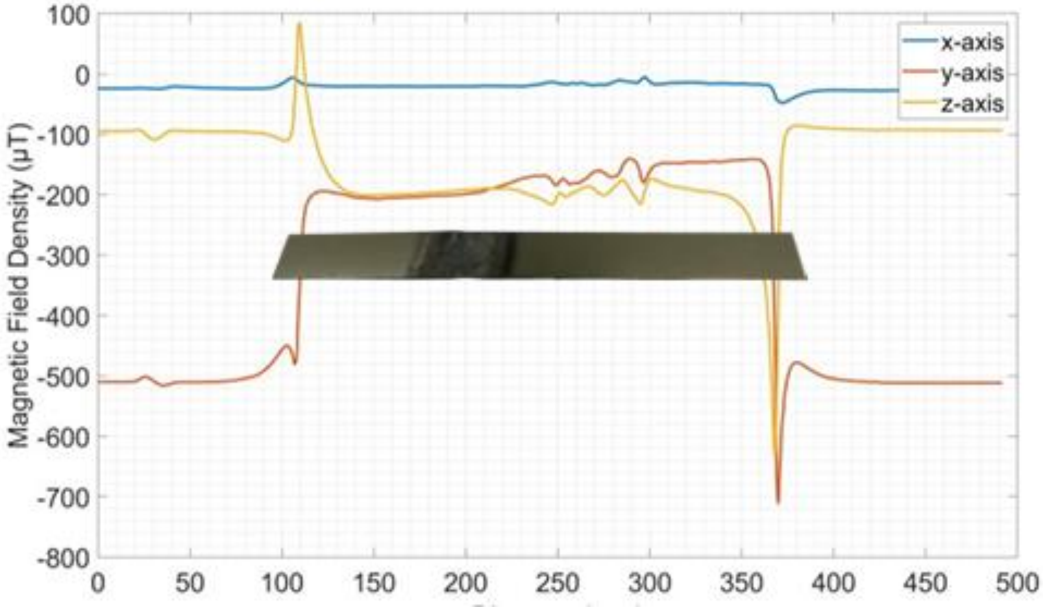

Figure 6: 3D AMR response with the biasing DC magnetic yoke. (steel element in physical dimensions with respect to distance measurements)

[‡] Barkhausen jump is the sudden overpassing of a stress field, after energy accumulation, resulting in hysteresis effects in steels.

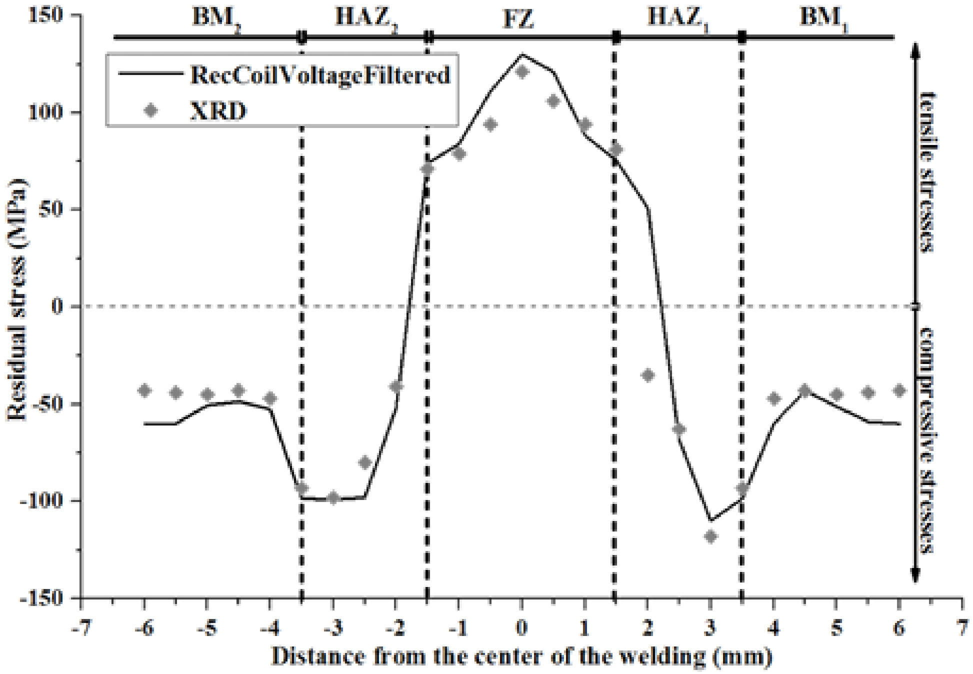

Figure 7: Correlation of residual stresses (dot points) with local differential magnetic permeability (continuous line, considered in arbitrary units) [15].

The AMR sensor's response indicates an almost linear dependence of residual stresses with the magnetic permeability.

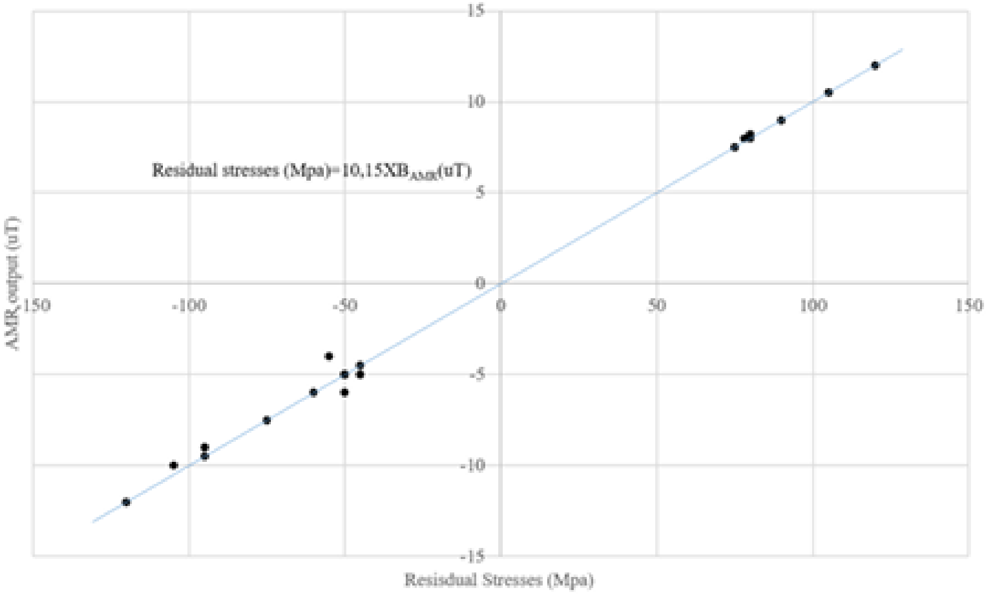

Figure 8: Dependence of residual stresses (MPa) on the AMR response (uT).

4 Conclusions

A new method for the determination of the magnetic stress calibration (MASC) curve is proposed in this paper, related to an advanced method of inducing residual stresses in magnetic steels, following localized induction heating and consequent quenching, allowing for MASC curve, suffering from much less uncertainties and having larger span with respect to stresses. The use of an AMR sensor appears to be promising for a distant detection of the localized residual stresses in different types of magnetic steels including 42CrMo4 steels

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