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ABSTRACT

The dependence of residual stresses on differential permeability, determining the so called Magnetic Stress Calibration (MASC) curve, results in the Universal MASC curve after normalizing the stress and permeability axes with the yield stress and the maximum differential permeability of the steel under test, respectively. The motivation of this paper is to illustrate the ability of obtaining the MASC curve of an unknown steel just by measuring its yield stress and maximum differential permeability. The calculated MASC curve of an unknown type of steel, obtained by multiplying the stress and permeability axes of the Universal MASC curve with the yield stress and maximum differential permeability obtained by the stress-strain curve under simultaneous measurement of the permeability, was compared with the actual MASC curve of the same unknown type of steel determined by the classical method, with an agreement better than ±5%. The conclusion is that the actual MASC curve of an unknown type of steel can be determined just by a stress-strain measurement, with simultaneous determination of the maximum amplitude of the differential permeability.

I. INTRODUCTION

Residual stress or strain gradient monitoring is an important parameter to monitor the structural and conditional health of steels and steel structures. Mechanical and thermal loading during the manufacturing process or the lifetime of a steel structure introduce strains. Beyond the yield point, plastic deformation begins due to dislocation motion. Nano- and micro-cracks may form and propagate, eventually leading to material failure. It is therefore important to monitor the evolution of residual stress or strain gradients over time while still in the elastic region. Furthermore, a sharp spatial gradient in residual stresses even before the yield stress is more likely to lead to a crack being generated than a uniform distribution of higher residual stresses.[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]

In the case of steel materials and structures which exhibit magnetic properties, magnetic methods have also been proposed and researched as an alternative or complementary to the above.[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] Using low excitation frequencies, in the order of 0.1 Hz up to 1 Hz, the effect of eddy currents is minimized and any

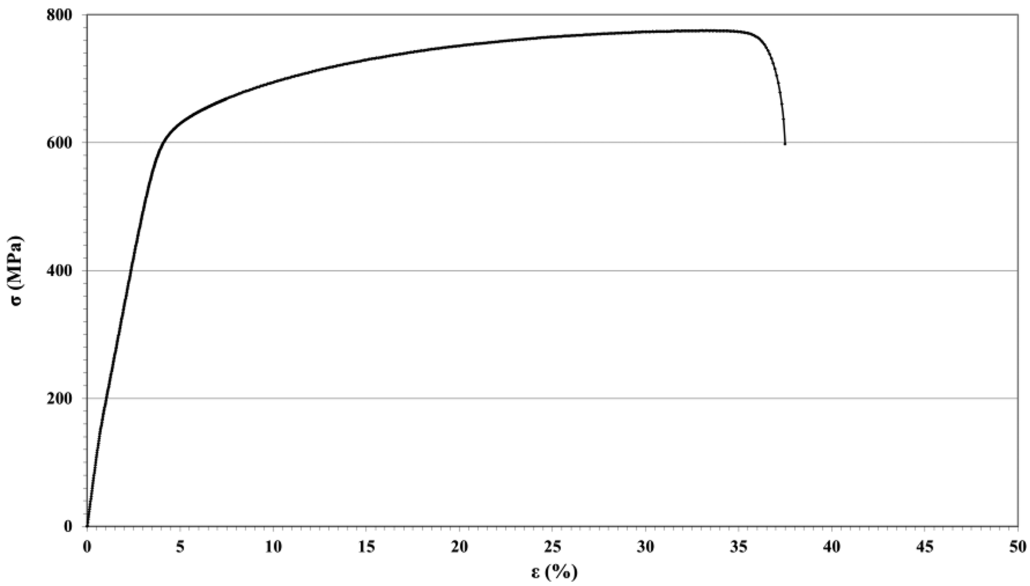

FIG. 1. The stress–strain curve of the unknown type of steel; it resembles the response of a duplex steel with the yield point at 595 MPa.

changes observed are related to microstructural non-uniformities and residual stresses.

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 tedious process which needs to be done 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]

This is an important result since the universal MASC curve may be used to obtain the MASC curve for an unknown steel sample, without going through the whole tedious MASC process. The stress-strain curve provides the yield point, while the differential permeability measurement provides the maximum amplitude of the differential permeability of the steel under test. The remainder of this work is devoted to demonstrating the potential of this technique.

II. EXPERIMENTAL AND DISCUSSION

The first objective of the article has been the reconstruction of the universal MASC curve, by obtaining the MASC curves for five (5) different ferromagnetic steels, namely non-oriented electric steel (NOES), Armco, AISI 1008, AISI 1431 and St37. All samples have been delivered in the form of rectangular plates of 100×150 mm^2 and thicknesses of 0.2 mm for the electric steel, 1.0 mm for the Armco steel, 0.5 mm for AISI 1008, and 2.0 mm for AISI 1431 and St37. All samples were cut in the middle in order to create two samples of 100×75 mm^2. Next, they were welded by Tungsten Inert Gas (TIG) welding, followed by X-ray inspection to check for cracks and make sure none were detected.

The surface residual stress components across the fusion zone, the two heat affected zones and the base material were determined through X-ray diffraction in the Bragg-Brentano (XRD-BB) set-up, using the Brucker D8 Advance XRD machine equipped with a Mo source. The stress monitoring area was a spot of 2 mm. After the determination of the residual stresses across the weld, the surface magnetic permeability was determined by our surface permeability sensor[12] at the same spots. Hence, for each spot across the weld, we obtain a pair of values: the residual stress and the corresponding magnetic permeability. Plotting these values for each different steel, resulted in five respective MASC curves. The uncertainty of the MASC determination due to the uncertainty of the permeability and residual stress measurement has been determined ±1% and ±2% respectively, resulting in a total uncertainty of about ±3%. The relatively low uncertainty of the residual stress determination was attributed to the Mo source of X-rays.

The normalization of each curve was realized by determining the yield point and the maximum differential permeability in all five steels, using a 100 kN Instron 4482 machine and our surface permeability sensor.[12] The experiments were realized as described in Ref. 11. As expected, all different MASC curves were collapsed in a single sigmoid response after the above mentioned normalization process. The maximum variation between the five different MASC curves after normalization has been determined at ~±5%. This result is in quite good agreement with the universal MASC curve presented in Ref. 11.

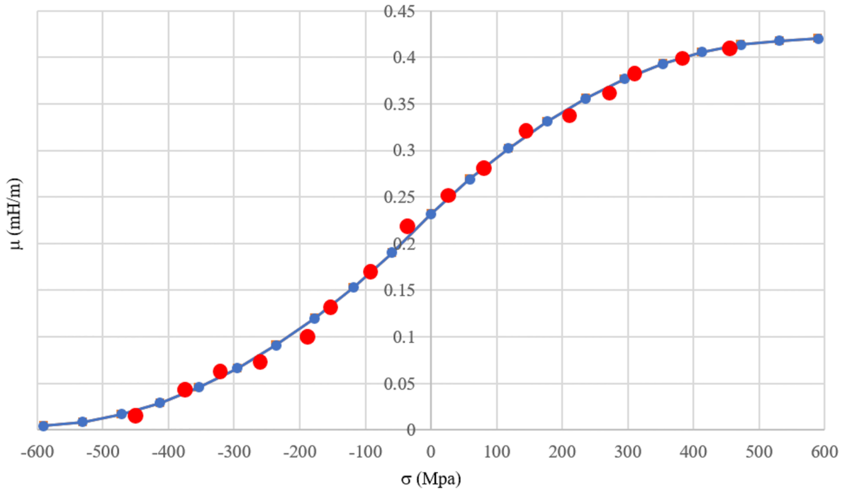

FIG. 2. Comparison of the actual MASC curve measured by the XRD-BB method and our surface permeability sensor, with the calculated MASC curve. The difference in response was calculated to be less than 5%. Small circles and fitting curve illustrate the calculated MASC curve, while large circles illustrate the pairs of measured values of residual stresses and differential permeability.

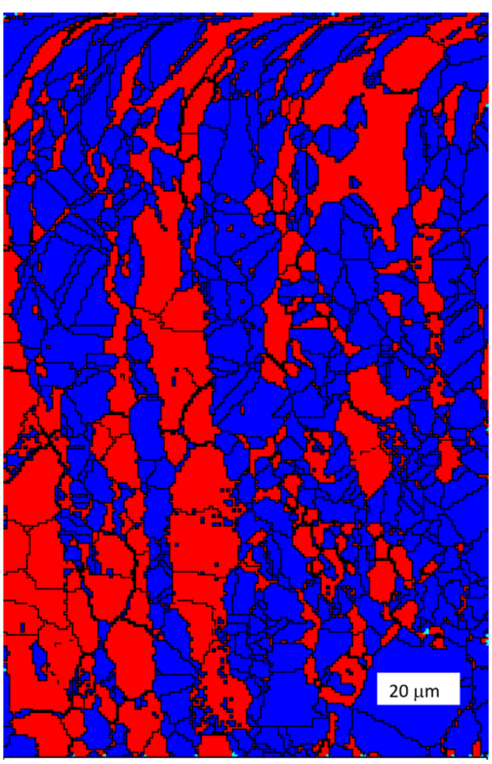

FIG. 3. Electron back scattering diffraction (EBSD) from a scanning electron microscope, illustrating a duplex steel microstructure in the unknown steel sample. The 20 μm scale bar is the white rectangle. The blue phase is ferrite and the red martensite.

The new universal MASC curve was used to obtain the MASC curve of an unknown steel sample. Two plates of the same unknown steel were received in dimensions of 100 × 150 mm^2. One of them was used for the determination of the yield point and the maximum permeability of the unknown steel, using a 100 kN Instron 4482 machine and our surface permeability sensor, after cutting the steel plate in a dog bone shape according to the standard ISO 527. The stress-strain curve is illustrated in Fig. 1 and resembles the response of duplex steel, judging from the shape of the stress-strain response and the yield stress, σ_y = 595 MPa. The measurement of the surface differential permeability equals 0.42 mH/m. Multiplying the X-axis with σ_y = 595 MPa and the Y-axis with 0.42 mH/m, the calculated MASC curve of the unknown steel has been determined.

To compare the calculated MASC curve with the actual MASC curve of the unknown type of steel, the second sample of the unknown steel was used. It was cut into two pieces of 100 × 75 mm^2 each and then welded using TIG welding. The welded sample was inspected by radiography to verify the absence of cracks in the fusion zone and the heat affected zones. Then, the residual stresses were determined by XRD-BB measurements across the weld at spots of mean diameter of 2 mm, while the differential permeability was measured at the same spots using our surface permeability sensor. The resulting pairs of values of residual stresses and surface permeability, represented as large circles, together with the calculated MASC curve (small circles and fitting curve) are illustrated in Fig. 2, demonstrating a maximum calculated variation between the calculated and the actual MASC curve of 5%. The comparison illustrates a relatively good agreement between them, demonstrating the applicability of the method for unknown types of steel.

Electron back scatter diffraction (EBSD) was used to spatially map the phases present in this alloy, using a JEOL6380LV scanning electron microscope (SEM), equipped with a Thermo Fisher Scientific EBSD detector. The results of the EBSD mapping, illustrated in

Fig. 3, clearly show the presence of a duplex steel microstructure, which is in agreement with the stress - strain curve.

From the above described experiments, it is clear that the method of determining the MASC curve of an unknown steel by just determining the yield point and the maximum differential permeability, using a stress – strain machine, can be applicable.

Experiments using other types of steel will be used in the near future to confirm the results achieved in this paper. Future work is also underway to holistically study such permeability dependence on field, that may open new ways in microstructural characterization.

III. CONCLUSIONS

In this paper the universality law of magnetic permeability on residual stresses has been revisited and verified. The particularly interesting result has been that the determination of the yield point and the maximum permeability of an unknown type of steel is enough to determine the actual MASC curve of the unknown steel within 5% error. The results were verified by following the classical method of residual stress and permeability determination for the MASC curves in an unknown type of steel, with an uncertainty less than ±5%.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Eleni Mangiorou: Conceptualization (equal); Data curation (equal); Investigation (equal); Methodology (equal); Writing – original draft (equal). **Tatiana V. Damatopoulou**: Investigation (equal); Resources (equal); Software (equal); Visualization (equal). **Spyridon Angelopoulos**: Formal analysis (equal); Investigation (equal); Methodology (equal). **Konstantinos Kalkanis**: Data curation (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal). **Polyxeni Vourna**: Data curation (equal); Formal analysis (equal); Methodology (equal); Resources (equal); Visualization (equal). **Aphrodite Ktena**: Conceptualization (equal); Methodology (equal); Supervision (equal); Writing – review & editing (equal). **Evangelos Hristoforou**: Conceptualization (equal); Data curation (equal); Methodology (equal); Resources (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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