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ABSTRACT

This paper explores the possibility to measure changes in internal stress in ferromagnetic steels using magnetostatic methods. The device consists of a permanent magnet placed close to the steel piece and a magnetic probe between both elements. The magnetostatic field measured by using the probe is partially due to the magnetization of the steel piece. Internal stress variations in the steel alter its magnetic permeability due to the magnetoelastic effect, varying the magnetostatic field measured by using the probe. For the device we present here, the relative variation of the measured magnetic field is of the order of 1.7×10^{-5}/MPa of internal stress.

INTRODUCTION

Steel is an excellent structural material due to its strength, ductility, hardness, impact resistance, and fracture toughness[1,2] and is commonly used in civil and mechanical engineering for buildings, bridges, railway infrastructures, and vehicles, among others.[3] The integrity of steel based structures requires not to overcome the elastic limit of the material. Hence, in critical cases and, especially, when external loads may have significant changes, the measurement of internal stress of structures made of steel becomes mandatory to ensure its integrity and safety. This internal stress may vary when the structure is in service due to the changes in the load distribution, thermal dilatations, oxidation, and others.[4] Consequently, non-invasive methods for the *in situ* measurement of changes in internal stress are required to prevent failure and increase the structure lifetime.

There are different methods to measure internal stress in steel structures in service.[5–8] X-ray and neutron diffraction are reliable methods,[9,10] but they cannot be commonly applied *in situ*. The strain gauge method appears to be simple, but it is limited to measure the surface local strain, which is subsequently related to local stress.[11] Ultrasonic methods have been shown to be accurate,[12] but they require direct contact and surface preparation, which is not always possible.

Magnetic methods can also give accurate information about the internal stress provided that the material is ferromagnetic at room temperature, as it happens for most of the steels used in civil engineering.[13] These magnetic techniques are based on magnetoelastic coupling. Mechanical deformation induces changes in the atomic distances and, therefore, in the electronic configuration and density of states of the material, which is ultimately responsible for the magnetic properties of the material.[14] Hence, the measurement of the magnetic properties of a material may provide information about the internal stress.

There are different sensors based on measuring hysteresis loops, and they detect variations in remanence, coercivity, or other parameters of the loop.[15] Magnetoacoustic sensors detect the emission of acoustic waves associated with the jumps of domain walls

(Barkhausen effect), which are sensitive to the local stress.[13,16] Other types of AC magnetic field sensors measure the dependence of acoustic wave velocity on the applied field, which is affected by local stress.[13,17]

The use of AC fields can be problematic in some cases, as it may require large power sources and can induce non-desirable currents or interferences, rendering it difficult for *in situ* measurement or making the sensor economically non-viable. In addition, the use of high frequency reduces the penetration depth and limits the information to the surface. Consequently, sensors using DC magnetic fields have also been investigated. Residual magnetic field sensors initially developed to ensure proper demagnetization of steel pieces can also be used to detect internal stress, although the level of measured magnetic fields (typically microteslas) makes it difficult to detect them out of the lab.[18,19] Sensors based in magnetic fields created by permanent magnets have been developed for measuring stress in steel cables,[20] but little work has been done for macroscopic pieces.[21]

This paper presents a non-invasive sensor for the measurement of variations of internal stress in macroscopic steel pieces, using a permanent magnet as a field source, which is simple and economic. This type of sensor could be interesting to detect stress in structural elements that are subjected to load fluctuations due to external or atmospheric conditions.[22,23]

EXPERIMENTAL

The scheme of the system is depicted in Fig. 1. A permanent magnet is placed close to the steel piece and oriented in such a way that it becomes partially magnetized. A Hall probe is placed in the region between the permanent magnet and the steel piece. The magnetic field (B) in this region will have two contributions, one from the permanent magnet and the second one due to the magnetization

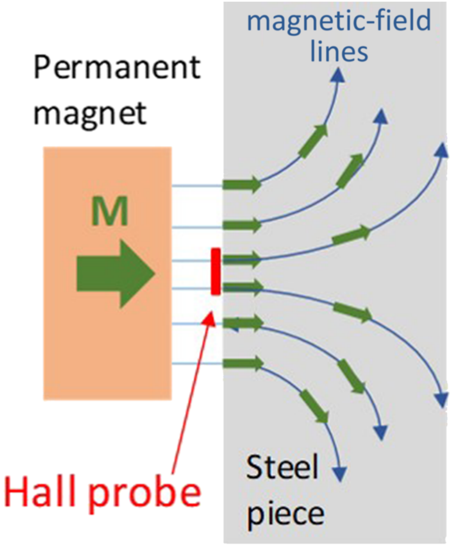

FIG. 1. Scheme of the device with the magnetic fields.

of steel. Since the magnetic permeability of the steel depends on its internal stress (Villari effect), the total magnetic field detected by the probe will also be dependent on this internal stress.

The type of permanent magnet, dimensions, and distances must be selected to have maximum sensitivity. Placing the magnet very close to the steel piece will lead to larger magnetization of this later and, consequently, to larger variations of the magnetic field measured by using the sensor because of internal stress. However, in this situation, the contribution to the magnetic field of the magnet will be very large, so relative variations will be weaker. On the other hand, placing the magnet far away from the steel piece will induce weak magnetization of the steel, so the total variations of the magnetic field detected by using the sensor will be small. Hence, a compromise must be achieved by selecting the appropriate distance between the magnet and the steel.

In order to experimentally prove the concept, a cylindrical NdBFe magnet with 20 mm diameter and 8 mm height was used (Fig. 4). The steel specimen used for the experiments was also a cylinder of steel 26CrMo4 [4130 Society of Automotive Engineers (SAE) grade] with 25 mm diameter and 100 mm height. A plastic piece fabricated using a 3D printer was used to set all components together. The Hall probe was a FH-55 teslameter by Magnet Physik with a transversal probe. A home-made program in Visual Basic was used to record the magnetic field as a function of time by connecting the analog output of the probe to a multimeter Keithley 2000. The distances between the permanent magnet–Hall probe and Hall probe–steel piece were 2.2 mm and 3.3 mm, respectively. The magnetic field created by the magnet at the Hall probe was 0.223 T while in presence of the steel piece, it turned to 0.296 T, indicating that at about ~25% of the field was due to the steel magnetization, and consequently sensible to induced stress.

In order to measure the variations of the magnetic field with the changes in internal stress on the steel piece, we used an electromechanical universal tester EM2/200/FR from *Microtest* to apply compressive stress. The system allows us to record stress–strain curves with controlled stress or strain rate.

The device was placed in the mechanical tester, as shown in Fig. 2. After some time, for mechanical stabilization in the absence of applied stress, the magnetic sensor recorded the magnetic field with relative fluctuations of the order of $5 \cdot 10^{-6}$. However, the motor of the tester load cell induced a continuous drift of the magnetic field measured by using the sensor even in the absence of load, and this may probably be due to the vibrations that slightly displaced the sensor head with respect to the steel piece, which had to be corrected.

RESULTS

The magnetic field was measured during a load cycle by increasing the load up to 100 kN (i.e., 203 MPa) and then returning to 0 kN for a total period of 800 s. The time dependence of the applied compressive stress is presented in the inset of Fig. 3. The main panel in Fig. 3 represents the measured magnetic field as a function of time during the load cycle after subtracting the linear background to account for the drift. It shows that both load and magnetic field show the same trend with time, indicating that the effect of the changes in internal stress is reflected on the variation of the magnetic field measured by using the Hall probe.

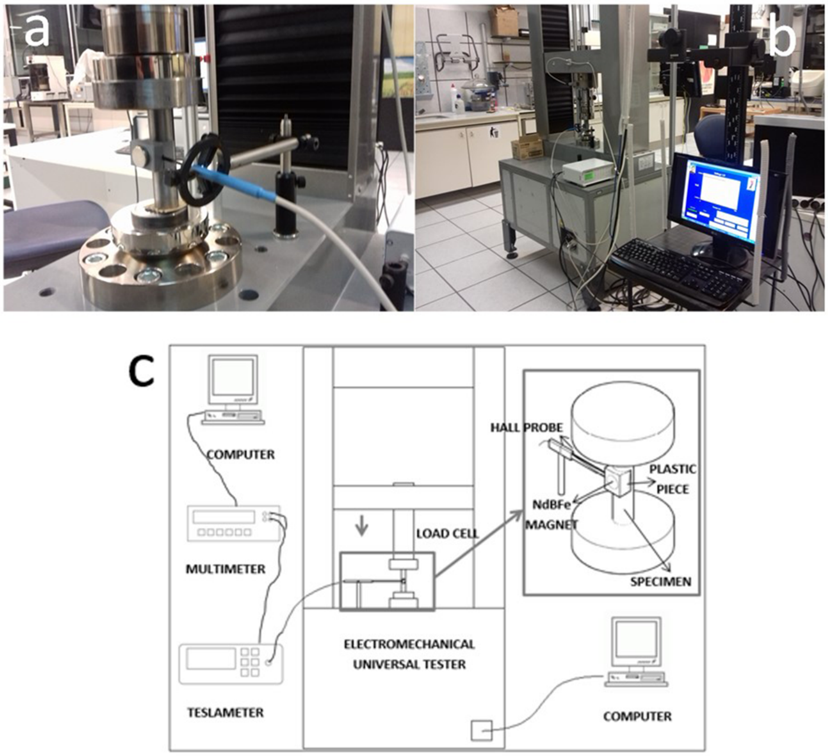

FIG. 2. (a) Sensor installed in the electromechanical tester with the Hall probe, (b) general view of all the measurement setups, and (c) sketch of the experimental setup.

However, some features and differences between the profile of the measured magnetic field and that of the applied stress are observed. The magnetic field curve and the stress do not have the same exact shape, indicating that the level of noise and/or other not controlled parameters that affect the measured magnetic field is not negligible. Hence, these data only allow estimating the effect, but they do not provide an accurate result.

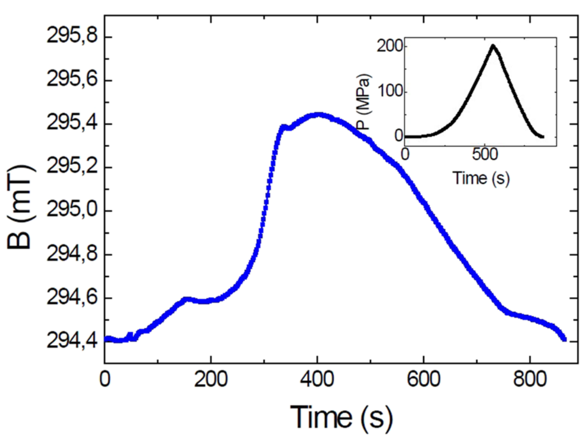

FIG. 3. Measured magnetic field as a function of time during the load cycle is presented in the main panel, and the time dependence of the applied compressive stress is presented in the inset.

These results show that a load of 200 MPa induces variations of the magnetic field measured by using the Hall probe of 1 mT, that is, relative variations of about $\sim 3 \cdot 10^{-3}$ of the magnetic field.

Therefore, it can be concluded that the sensitivity of the method (i.e., relative variations of the measured magnetic field) is of the order of $\sim 1.7 \cdot 10^{-5}$/MPa. This value may obviously present some variations depending on the particular configuration and geometry of the designed sensor, but, as an estimation of the order of magnitude of the sensitivity achievable with this type of device, it is valid.

In order to confirm the experimental data, a numerical simulation was performed using the finite element method. For this purpose, the COMSOL software was used. The dimensions and spatial distribution of the magnet and the steel specimen were the same as those in the experiment. Figure 5 represents an illustration of the magnetic field distribution obtained from the simulation. The region of the steel specimen becomes partially magnetized due to the presence of the ferromagnet. The magnetic field between both pieces (i.e., where the Hall probe was placed) has two contributions, one due to the ferromagnets and another due the magnetization of the steel; this is shown in Fig. 4.

The value of the magnetic field at the position of the Hall probe is about 0.3 T, in agreement with the experimental measurements, confirming the reliability of the simulation.

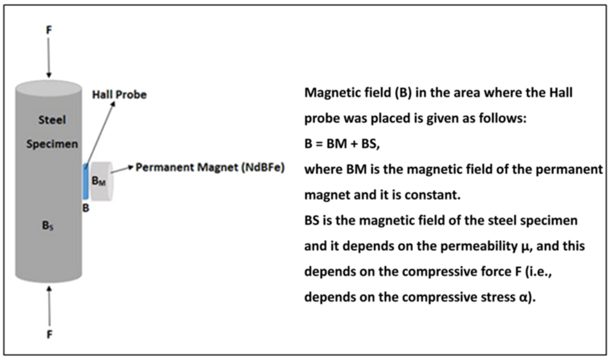

FIG. 4. Scheme of the test device and value of the magnetic field (B) in the area where the Hall probe was placed.

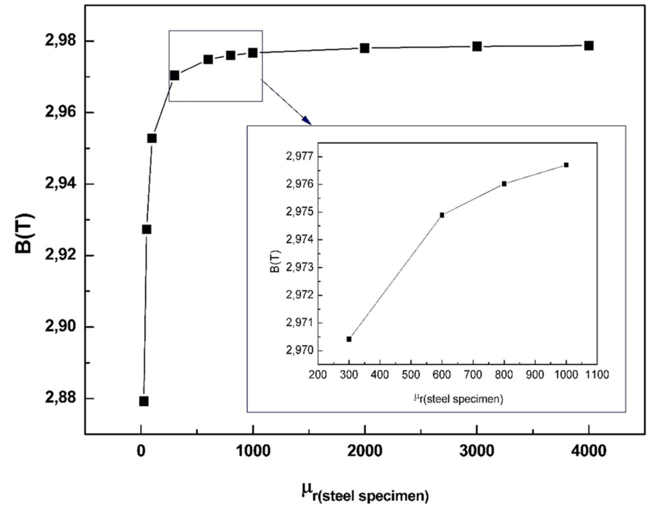

FIG. 6. Magnetic field at the position of the Hall sensor as a function of the permeability of the steel obtained from the simulations.

The simulation was repeated for different permeability values of the steel specimen ranging between 0 and 4000 (25, 50, 100, 300, 600, 800, 1000, 2000, 3000, and 4000). Figure 5 represents the results. As expected, the magnetic field at the sensor position increases with the permeability of the steel (see Fig. 6). After a rapid increase, there is a kink for the permeability of the order of 100, and then, the slope is strongly reduced. This is due to demagnetizing the field that reduces the magnetization of the steel.

For the permeability of the steel used in the experiments (over 600), the slope of the curve is about $1.8 \cdot 10^{-4}$ T and the slope of the inverse curve is ~$5.55 \cdot 10^{3}$ T^{-1}.

In the experiments, the increase in magnetic field upon the application of 200 MPa compressive stress was 1 mT, and therefore, this should lead to a variation of the permeability about 5.55, that is, $\Delta\mu/\mu \approx 10^{-2}$ for 200 MPa. This result is consistent with those reported in the literature for AISI-type steels.[24]

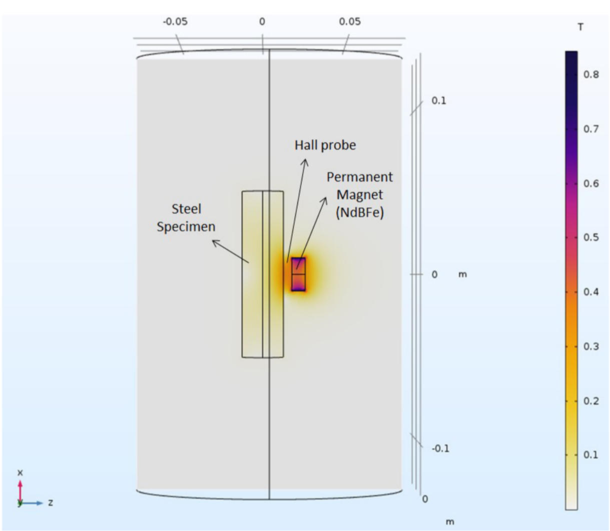

FIG. 5. False-color image of the value of the magnetic field calculated using the finite element technique.

CONCLUSION

In summary, a simple, economic, and non-invasive magnetic sensor for the measurement of the changes in internal stress in pieces of steel was presented. The sensor consists of a permanent magnet and a Hall probe connected by a piece of plastic fabricated in 3D. The Hall probe was placed between the steel specimen and the magnet in this area, and the magnetic field has two contributions, one due to the magnet and another due to the magnetization of the steel specimen. The magnetic permeability of the steel depends on the internal stress. Therefore, the sensor would be able to provide an estimation of the mechanical stress as the contribution of the steel specimen to the total magnetic field detected by using the Hall probe varies when subjected to different stresses.

The proof of concept was carried out experimentally using some specific samples and the magnet. The magnetic field created by the magnet is 0.223 T, but with the presence of the steel, it became 0.296 T; this indicates that 25% of the field is due to steel magnetization. In this particular case, the relative variation of the measured magnetic field was ~$1.7 \cdot 10^{-5}$/MPa. The simulations carried out using numerical models are consistent with the results obtained in the tests.

The question of the applicability of this concept to a particular case still stands as other points will need to be addressed such as resolution, repeatability, drift, signal/noise ratio, linearity, etc. These will be dealt with when a sensor for a specific application will be developed using the concept illustrated in this paper. Depending on the particular application, the required sensitivity in the determination of the internal stress will infer the required precision in the measurement of the magnetic field and determine whether the concept is applicable or not.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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