Stress state evaluation in low carbon and TRIP steels by magnetic permeability

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Abstract. Magnetic permeability is an indicative factor for the steel health monitoring. The measurements of magnetic permeability lead to the evaluation of the stress state of any ferromagnetic steel. The magnetic permeability measurements were conducted on low carbon and TRIP steel samples, which were subjected to both tensile and compressive stresses. The results indicated a direct correlation of the magnetic permeability with the mechanical properties, the stress state and the microstructural features of the examined samples.

1. Introduction
Steel is described as an industrial iron - carbon alloy, where the weight content of carbon ranges from 0.025 %w/w to 2.1 %w/w. In steels, various phases are shown, due to the allotropic behaviour of iron and to the complex heat treatments, during the manufacture of steel. Some of these phases, such as ferrite, perlite, martensite, and bainite, exhibit ferromagnetic behaviour [1].

It is clear that steel is a composite ferrous metal alloy with varying mechanical properties, which impart a wide range of applications. However, the different parts of a structure made of steel need to be systematically checked, in order to determine their condition. This control is carried out by various techniques, either destructive or non-destructive [2-11]. The magnetic permeability measurement technique is included among the non-destructive techniques; however, this method is still in laboratory level [11-22].

Conclusions about the characteristics of the material and its structure can be derived by the analysis and study of the output signal of this magnetic sensor. This method can detect defects on the material surface, or throughout the mass, without requiring special preparation of the specimen. Of course, as a method of magnetic non-destructive testing, it is limited to ferromagnetic materials with relatively smooth surfaces, preferably without paint or other coatings.

In recent years, the interest of researchers has grown around the application of magnetic methods in determining the stress condition of steels. However, there is a limited number of published articles on the determination of residual stress using the magnetic permeability method [12-13, 16-17].

For this reason, the magnetic permeability measurements were conducted on low carbon and TRIP steel samples, which were subjected to both tensile and compressive stresses, and thereby there is a direct correlation of the magnetic response values to those deriving from the mechanical stresses inherent in the material.
2. Experimental procedure

2.1. As received materials

In the present article two types of steel are studied: the first was low carbon steel type St37-2 and the second TRIP. The dimensions of the samples were 20cmL x 15cmW x 0.15cmT. The chemical composition of each steel type is presented on table 1.

|          | C     | Mn    | Si    | P       | S       | Fe       |
|----------|-------|-------|-------|---------|---------|----------|
| St37-2   | 0.090 | 0.520 | 0.010 | 0.019   | 0.007   | Balanced |
| TRIP 800 | 0.195 | 1.64  | 1.58  | -       | -       | Balanced |

2.2. Magnetic measurements

Two sensors for the magnetic permeability measurement: one was identifying the surface magnetic response in St-37 steel, while the second was identifying the bulk magnetic permeability of the TRIP 800 steel.

The magnetic sensor for the determination of the surface magnetic permeability used in the laboratory is shown in Figure 1(a). The sensor is excited by a sinusoidal signal of 1KHz frequency by a function generator. The excitation and reception signal is received by a NI PXI system data acquisition card (DAQ), in order to be processed (filtering output signal, graph display) in LabView environment. The receiving coil is wounded around an electromagnet, resulting in obtaining the surface’s output signal. The maximum value of this voltage is the representative value of the surface magnetic permeability, at the point of measurement in St-37 grade of steel.

The laboratory magnetic sensor, which is used in order to determine the bulk magnetic permeability is illustrated in Figure 1(b). An alternating sinusoidal voltage pulse (amplitude 1V, frequency 1Hz), is applied to the excitation coil. The change in magnetic flux, due to the presence steel, is measured by a receiving coil located on the one leg of the electromagnet. The output voltage of the magnetic sensor is proportional to the magnetic permeability of the TRIP 800 steel. The absolute value of the output signal’s total maximum is the examined magnetic parameter.

![Figure 1](a) ![Figure 1](b)

Figure 1. Magnetic measurement sensors for (a) the surface and (b) the bulk magnetic permeability.

The samples have to be calibrated, in order to determine their residual stress values. Therefore, tensile and compressive tests, at preselected deformation steps within the elastic region, took place. The direction loading tests is parallel to the rolling direction, in both samples. Dog-boned samples are cut from the as-received ones, according to the ASTM E8 standard.

At each pre-defined deformation step, five magnetic values were recorded and averaged. These averaged values represent the corresponding magnetic parameter. During the experiment, the stress values were recoded. The completion of the above process led to the determination of the calibration curve of the samples. Through this curve, it was possible to assign the magnetic parameter to the values of residual stresses in the studied material.
3. Results

The correlation between the applied stresses (either tensile or compressive) is possible, taking as parameter the total maximum of the magnetic sensor’s output waveform. This is illustrated as a calibration curve (figure 2 and 3).

![Figure 2. Calibration curves of St 37-2 steel grade.](image1)

![Figure 3. Calibration curves of TRIP 800 steel grade.](image2)

Steels are positively magnetostrictive. The presence or absence of applied stresses cause the rearrangement of the magnetic domains, in such a way as to minimize the magnetoelastic and the anisotropy energy. When the direction of the applied stress differs from the magnetization orientation or the number of the 180° domain walls is increased the total energy of the magnetic configuration is minimized [23-27].

Thus, in stressed samples, the initial easy axis magnetization rotates, in order to become parallel to the direction of the applied stress. Therefore, the magnetization vectors of a ferromagnetic material under tensile stresses, which are considered as positive stresses, is aligned towards the direction of the external stress, resulting in the increment of the 180° domain walls. On the contrary, compressive stresses, which are considered as negative stresses, tend to align the magnetization vector perpendicular to the stress axis. As a result, regarding a positively magnetostrictive ferromagnetic alloy, the tensile stresses increase the magnetic response, while the compressive ones reduce it (figure 4 and 5).

The differences of the calibration curves of St-37 low carbon steel and the TRIP steel, within the elastic region, are interpreted on the basis of the changes in the microstructures. The St-37 is a common ferrite-pearlite steel (figure 4), while the Transformation Induced Plasticity steel represent a family of multiphase steels (figure 5). TRIP steel consists of a mixture of ferrite and bainite and what seems to retained austenite.

![Figure 4. SEM micrograph of St-37 steel grade.](image3)

![Figure 5. SEM micrograph of TRIP 800 steel grade.](image4)
4. Conclusions
Surface and bulk magnetic permeability measurements potentially can be used as non-destructive evaluating methods for estimating the stress state in a ferromagnetic material's. The variations of the magnetic permeability values are sensitive to the microstructural characteristic of the ferromagnetic steels.

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