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A novel approach of accurately evaluating residual stress and microstructure of welded electrical steels

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ABSTRACT

In the present research work the determination of residual stress distribution in welded non-oriented electrical steel samples is discussed. Tungsten inert gas was used for the welding method. Residual stress was directly determined through deformation measurements and appropriate math calculations. Two methods were used: the magnetic, non-destructive method of Barkhausen noise and the semi-destructive method of X-ray diffraction. In order to evaluate the accuracy and reliability of the magnetic method applied, the steel samples were subjected to both compressive and tensile stresses and the magnetic noise values were correlated to residual stress values through an appropriate calibration curve. The results were then verified by the XRD method and were further evaluated by examining the microstructure and the mechanical properties of the as received and welded samples through scanning electron microscopy and hardness measurements, respectively. It was found that the deviation between the two methods was within acceptable limits, thus implying potential applicability of the MBN method in non-destructive testing of materials.

1. Introduction

Stresses within a material are broadly divided into two main categories (a) internal and (b) external stresses. External stresses are related to external forces applied on a material. On the other hand, internal stresses are intrinsically present within the material, even if there are no external forces acting on it. Internal stresses are of particular interest since they largely affect the macroscopic properties of the material. The part of stress, which is below the yield stress, remains within the material as residual stress.

A considerable amount of residual stresses is introduced during common manufacturing processes. These stresses are caused by mechanical loads, temperature gradients and volumetric changes due to solid state phase transformations, which result in an inhomogeneous plastic deformation process. Depending on their magnitude and distribution, residual stresses are rather useful in elucidating possible causes of failure of a material.

During welding, the temperature range varies from the material's melting point to the room temperature. Additionally, the mechanical properties of the joint are temperature dependent, and therefore these are often degraded due to the presence of thermal gradients. Cooling to room temperature invokes stresses, which are inevitably incorporated to the material's residual stress. Therefore, the quantitative determination of the residual stresses is important for the quality, integrity and performance of the welding joints.

Since stress is an extrinsic property and cannot be directly estimated, all methods applied so far take into account an intrinsic property, such as strain, and then the residual stress can be therefore easily calculated.

The methods which are appropriate for measuring residual stresses are broadly classified into two main categories: destructive (e.g., hole-drilling) and non-destructive (X-ray and neutron diffraction, ultrasonically, recently by Raman, etc.) methods. Each of these methods has its own advantages and disadvantages [1].

As far as the advantages of the aforementioned methods is concerned, both X-ray (the most widely used technique for residual stress evaluation) and neutron diffraction can be applied either in metallic or non-metallic material. Moreover, by the ultrasonic method bulk residual stresses can be on-site evaluated. This method is quite flexible and is commonly used at an industrial level. On the contrary, the Raman method is mainly used in laboratory scale and presents the most reliable results among the above mentioned methods.

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However, all these methods are also characterized by important disadvantages and physical limitations. The XRD method, for example, requires highly trained scientific personnel for the evaluation of the results. Second, the sample needs a special treatment prior to application of the method. The calibration of the diffractometer has to be precise too and the implementation of the method is, in general, time consuming. The neutron diffraction method has the same disadvantages and additionally, it is a rather expensive technique and its utilization is limited only to laboratory scale. As far as the ultrasonic method is concerned, the results are non-linear, while these are considered to be the least reliable when compared to the results of the other stress evaluation techniques. Finally, the Raman technique is yet at its infant stages of development, and therefore has to be thoroughly tested in order to find a broad utility. Highly trained scientific personnel for the evaluation of the results are required and on-site implementation is, for the time being, impossible. And once more, the utility of this method is limited to laboratory scale.

A viable alternative to the aforementioned methods for the evaluation of residual stress is the Magnetic Barkhausen Noise (MBN) method. The MBN method is especially suitable for ferromagnetic polycrystalline materials. It is a fast, reliable, economic method, which can be applied on-site. It is appropriate either for laboratory or for industrial scale. The test samples require no special pre-treatment. By determining the mechanical behavior of the material in either tensile or compressive loads the magnitude and the distribution of the residual stresses can be easily evaluated. An additional advantage of this method is that stress evaluation can be restricted within a single grain of the material.

Due to the above-mentioned advantages the MBN method can be rather useful in evaluating the stress of welded materials. In this way the residual stress state in each welding zone of the material may well be determined.

Several studies have been published [2–20] to describe the possibility of applying non-destructive magnetic techniques on the study of changes in the microstructure, grain size, stress state and plastic deformation in cold-rolled non-oriented electrical steels (NOES).

To the best of our knowledge, however, there is only limited literature [21,22] concerning the non-destructive estimation of the residual stress state in butt joint configurations of welded NOES samples. In reality, such literature concerns only simulations of the magnetic techniques' performance in order to investigate the microstructural changes in welded NOES.

In the present research work, stress measurements in Tungsten Inert Gas (TIG) welded NOES were recorded by both the Magnetic Barkhausen Noise and the X-ray diffraction methods.

For this reason, two identical sheets were welded together by TIG in a butt joint configuration, with the welding line direction being perpendicular to the rolling direction. The resulting residual stress, estimated by the magnetic technique, was compared with the values resulting from the XRD method in both the as-received and welded samples. The specimens were also characterized in terms of their mechanical properties. Finally, the fluctuations of residual stress on the surface of either the as-received or welded samples were evaluated on the basis of experimental evidence and micro-structural changes occurring during welding.

2. Materials and methods

2.1. Materials

The studied alloy was a commercial, fully-processed cold-rolled NO electrical steel sheet, with the chemical composition shown in Table 1. The dimensions of the reference specimen were $120 \times 60 \times 0.58\ \text{mm}^3$ (Fig. 1).

From the iron–silicon binary phase diagram [23], it was obvious that the microstructure of the as-received NO electrical specimens was a bcc-ferrite matrix. The same structure was retained at all temperatures up to the melting point.

2.2. Welding technique

Two identical sheets were welded together in a butt joint configuration, with the welding line oriented perpendicular to the rolling direction. The sheets were welded by TIG (Fig. 2). Argon shielding gas was supplied on the top of the surface at a rate of 18 l/min. The welding parameters (Table 2) were carefully selected in order to assure full penetration welds free of defects, such as porosity and cracking.

The dimensions of each one of the welding zones, namely, of the Base Metal (BM) zone, of the Heat Affected Zone (HAZ) and of the Fusion Zone (FZ) are illustrated in Fig. 3.

2.3. Residual stress measurements

Stress measurements on the surface of the test samples were conducted by the Magnetic Barkhausen Noise (MBN) and the X-ray diffraction (XRD) methods.

2.3.1. Magnetic Barkhausen Noise measurements

Szielasko et al. [24] examined the internal stress in thin coatings and on a variety of substrates by mapping the distribution of the Magnetic Barkhausen Noise on various regions of the coatings. This method correlated the magnetic noise with the internal stresses in the coatings, but it was neither applied on bulk materials nor concerned the welded steels. This means that the aforementioned method mostly considered surface effects. Secondly, the same method did not take into account extreme thermal gradients, such as those present during the welding. Moreover, the method which was used relied on repeatable monitoring of the MBN output signal in order to evaluate stress in each coating. In this work a different approach was attempted. This approach was based on the generation of a calibration curve, which would be characteristic of the specific steel grade examined regardless of the welding method. In this way, repeatable correlation of the MBN output signal with the steel's stress would be avoided.

As it is known, the MBN method is very sensitive to changes of both microstructure and applied stress (tensile stresses increase

Table 1
Typical chemical composition in wt% of commercial NOES.

Si	Al	Mn	C	P	S	Fe
2.18	0.35	0.12	0.0018	0.00009	0.00005	Balance

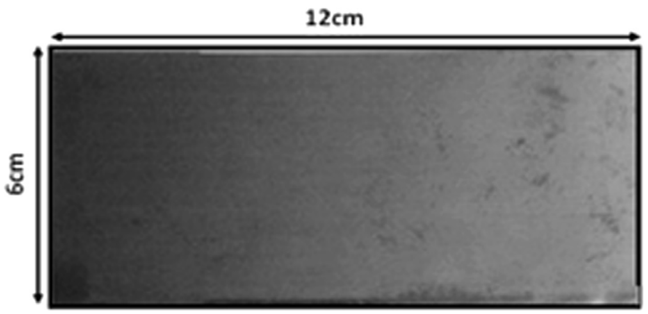

Fig. 1. Dimensions of the as-received cold rolled NO electrical steel samples.