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An accurate evaluation of the residual stress of welded electrical steels with magnetic Barkhausen noise

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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, Plasma and Electron Beam were used as the welding methods. 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 accuracy and reliability of the magnetic method applied, the steel samples were subjected in 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. Then, these were further evaluated by examining the microstructure and mechanical properties of as received and welded samples by scanning electron microscopy and macrohardness 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

The MBN signal contains information which is closely related to the microstructure [1–14] of an examined ferromagnetic material. Thus, any change in grains configuration, due to the presence of stresses [15–19] or of lattice distortions, results in rearrangement of the magnetic domains' configuration.

The fore mentioned dependence of the MBN to the material's intrinsic properties makes it a potential tool of non-destructive techniques (NDT), for the evaluation of metallurgical, microstructural, mechanical and micromagnetic parameters.

The major proportion 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.

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

Since the stress is an extrinsic property and cannot be directly estimated, all the methods adopted so far take into

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account an intrinsic property, such as strain, in order to evaluate the residual stress.

Literature survey reports broad utilization of the MBN technique in measuring residual stresses [20–27]. The MBN method is a fast, reliable, economic method, and it is appropriate either for laboratory of for industrial scale. The test samples require no special pre-treatment. Due to the above mentioned advantages, the MBN method can be well applied in stress evaluation 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 [28–42] to describe the possibility of applying non-destructive magnetic techniques on the study of changes in microstructure, grain size, stress state and plastic deformation in cold-rolled Non-Oriented Electrical Steels (NOES). Simulations of the performance of magnetic non-destructive techniques in order to investigate the microstructural changes in welded NOES have been carried out in the past [43,44]. To our knowledge however, the non-destructive estimation of the residual stress state in butt joint configuration of welded NOES has never been reported.

In the present research work, two identical NOES sheets were welded together in a butt joint configuration, with the welding line direction perpendicular to the rolling direction. The sheets were welded using Tungsten Inert Gas (TIG), Plasma and Electron Beam (EBW) as the welding techniques. Stress measurements were recorded in the surface of the welded samples using both Magnetic Barkhausen Noise and X-ray diffraction methods.

Table 1
Typical chemical composition of commercial NOES.

Element	Si	Al	Mn	C	P	S	Fe
wt%	2.18	0.35	0.12	0.0018	0.00009	0.00005	Bal.

The residual stresses, induced by welding estimated by the magnetic technique and were compared with the values resulting from the X-ray Diffraction (XRD) method. The fluctuations of the residual stresses in the welding zones of the welded samples are discussed on the basis of the experimental evidence and the microstructural changes occurring during welding. Finally, the specimens are characterized in terms of their mechanical properties.

2. Experimental procedure

2.1. Material

The studied alloy was a commercial, fully-processed cold-rolled NO electrical steel sheet. Its chemical composition is shown in Table 1. The dimensions of the examined specimen were 60 × 60 × 0.58 mm^3.

The as-received NOES steel specimen presented a ferrite matrix with microsegregation of silicon, especially at the grain boundaries. The ferrite grains had an average grain size of 47 μm ± 9 μm and a polygonal, equiaxed morphology. As far as its mechanical properties is concerned, the surface macrohardness value was around 105 Vickers, the longitudinal yield strength (YS) was ~290 MPa, and the Ultimate Tensile Strength (UTS) was ~370 MPa while the elongation was the order of 30%.

2.2. Welding techniques

Six NOES samples were first cleaned with distilled water and subsequently dried. Three pairs of identical NOES sheets were welded together in a butt joint configuration. The welding line was perpendicular to the rolling direction. No pre-weld heat treatment was performed in the as-received samples before welding. These three pairs of NOES steels were welded with three different welding

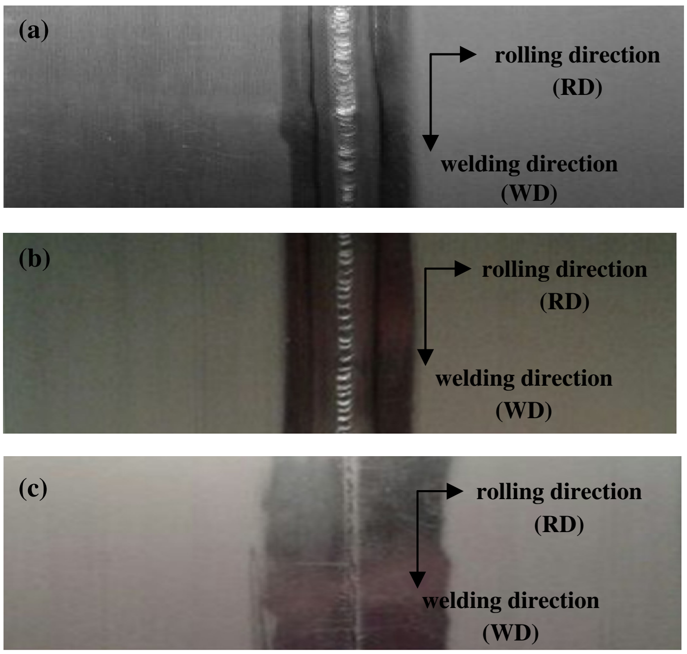

Fig. 1. Welded, cold rolled NOES samples using (a) TIG, (b) Plasma and (c) EBW as the welding techniques.