An accurate method for determining residual stresses with magnetic non-destructive techniques in welded ferromagnetic steels

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Abstract. The scope of the present research work was to investigate the proper selection criteria for developing a suitable methodology for the accurate determination of residual stresses existing in welded parts. Magnetic non-destructive testing took place by the use of two magnetic non-destructive techniques: by the measurement of the magnetic Barkhausen noise and by the evaluation of the magnetic hysteresis loop parameters. The spatial distribution of residual stresses in welded metal parts by both non-destructive magnetic methods and two diffraction methods was determined. The conduction of magnetic measurements required an initial calibration of ferromagnetic steels. Based on the examined volume of the sample, all methods used were divided into two large categories: the first one was related to the determination of surface residual stress, whereas the second one was related to bulk residual stress determination. The first category included the magnetic Barkhausen noise and the X-ray diffraction measurements, while the second one included the magnetic permeability and the neutron diffraction data. The residual stresses determined by the magnetic techniques were in a good agreement with the diffraction ones.

1. Introduction
Residual stresses can be defined as those stresses existing within a structural material or component, in the absence of any external loading or thermal gradients [1]. Among the factors that are known to cause residual stresses are the development of deformations, due to the application of mechanical loads or to the presence of thermal gradients. Moreover, the changes in volume during solidification or due to solid state transformation introduced residual stresses in a material [1-2].

A considerable amount of residual stresses is introduced during common manufacturing processes. Additionally, during welding the material is subjected to temperatures ranging from the material’s melting point to room temperature [3]. 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 dependant 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 [1-5]. Therefore, the quantitative determination of the residual stresses is important for quality, integrity and performance of the welding joints.

Although there are many scientific articles describing the correlation of magnetic and material’s properties [6-18], there are only few reports describing the determination of residual stresses via magnetic techniques.
magnetic techniques [19-35]. In addition, reports on predictions of the spatial distribution of the residual stresses in welded ferromagnetic samples are rather limited [1, 4-5, 21].

The scope of the present research work was to investigate the proper selection criteria for developing a suitable methodology for the accurate determination of residual stresses existing in welded parts. Magnetic non-destructive testing took place by the use of two magnetic non-destructive techniques: by the measurement of the magnetic Barkhausen noise and by the evaluation of the magnetic hysteresis loop parameters. The spatial distribution of residual stresses in welded metal parts by both non-destructive magnetic methods and two diffraction methods was determined. The conduction of magnetic measurements required an initial calibration of ferromagnetic steels. Based on the examined volume of the sample, all methods used were divided into two large categories: the first one was related to the determination of surface residual stress, whereas the second one was related to bulk residual stress determination. The first category included the magnetic Barkhausen noise and the X-ray diffraction measurements, while the second one included the magnetic permeability and the neutron diffraction data.

2. Experimental procedure

Three different grades of ferromagnetic steel were tested: non-oriented electrical steel (NOES), low carbon steel (AISI 1008) and low-alloyed carbon steel (AISI 4130). For each grade of steel, two identical sheets were welded together in a butt joint configuration by different welding techniques. The welding parameters were carefully selected to produce full penetration welds free of defects, such as porosity and cracking.

As far as the magnetic measurement set-up is concerned, two laboratory methods were used: the magnetic Barkhausen noise (MBN) and the magnetic permeability (MP). The apparatus used for the magnetic measurement has been described elsewhere [1, 3-5].

In order to evaluate residual stresses using the magnetic techniques, a two-step procedure is proposed. In the first step the as-received samples have to be cut in rectangular dog-bone-shaped flat specimens and then subjected both in tensile and compressive deformation, in a step-wise manner by a loading machine (INSTRON). For strain measurements, a commercially available strain gauge is adhered on the surface of the testing sample, at the centre of the gauge length. The measured strain values are converted to stress values through elasticity equations. While strain is measured, magnetic values is also recorded, using the appropriate magnetic sensor device. The root mean square (rms) value of the measured MBN signal, as well as the MP from the hysteresis loops are considered as estimated parameters. During the second step the distribution of the magnetic values is measured on the sample, taking measurements at pre-defined intervals along the length of the sample’s surface. The temporal fluctuations of the magnetic values yielded information about the spatial distribution of the residual stresses on the surface and bulk of the sample, with the aid of the calibration curve.

3. Results

In the NOES samples, which were welded together using TIG (figure 1) and Plasma (figure 2) as the welding techniques, the residual stresses determined by the MBN and the XRD method followed a similar trend. However, the residual stresses determined by the magnetic permeability method represented a deviation from the results of the XRD method. This was attributed to the different penetration depth of each method.

In order to confirm the accuracy of the aforementioned magnetic techniques in determining residual stresses, AISI 1008 samples were welded using electron beam (EB) as the welding technique welded (figures 5, 6). The residual stresses determined by all four methods presented only minor deviations. To further evaluate the effectiveness of the magnetic techniques in determining residual stresses, AISI 4130 samples were welded by either TIG (figure 7) or EB (figure 8) as welding techniques. It was confirmed that, with regards to the residual stresses the MBN followed a similar trend to the XRD, in both welded samples. Furthermore, the results from the permeability method were in a good agreement with the ND ones, in both welded samples.
Figure 1. Determination of residual stress with MBN and XRD methods in TIG welded NOES samples.

Figure 2. Determination of residual stress with MBN and XRD methods in Plasma welded NOES samples.

Figure 3. Determination of residual stress with MP and XRD methods in TIG welded NOES samples.

Figure 4. Determination of residual stress with MP and XRD methods in Plasma welded NOES samples.

Figure 5. Determination of residual stress with MBN and XRD methods in EB welded AISI 1008 sample.

Figure 6. Determination of residual stress with MP and ND methods in EB welded AISI 1008 sample.

Figure 7. Determination of residual stress with MBN and XRD methods in TIG welded AISI 4130.

Figure 8. Determination of residual stress with MP and ND methods in EB welded AISI 4130 samples.
4. Conclusions
Welding procedures were used to evaluate the effectiveness of the MBN and MP methods in determining the residual stresses. These methods were compared to the XRD and ND methods, respectively. The results indicated that the deviation between them was within acceptable limits. Thus, the magnetic techniques are reliable non-destructive methods for analysing existing stresses, but they require the precise calibration of the ferromagnetic sample.

5. References
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