MAGNETIC STEEL HEALTH MONITORING: ADVANCES AND CURRENT STATE OF THE ART

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Abstract: Steel industry is one of the larger market sectors in the today's world. Information provided by the World's Steel Association suggests that the total steel industry activity in Europe reflects the ~4.5% of the total European GDP, with China leading the world's steel production, manufacturing & use, with the ~5.5% of its GDP dedicated for this sector. At this moment, only residual stresses can be monitored in steel industry & steel products and only on the surface of these steels. Furthermore, their annihilation or control is based on principles and procedures based on the current international standards, without a feedback control system permitting for the precise monitoring and annihilation of the stress level distribution in all their volume.

Our technology permits the stress tensor distribution monitoring in the bulk and the surface of ferromagnetic steels, concerning the determination of their residual stresses and plastic deformation, by using magneto-elastic non-contact and non-destructive methods with an uncertainty better than 1%. The speed of stress monitoring can reach 30 m/s under certain circumstances. Therefore, the steel producer, manufacturer or user can quantitatively measure the precise amplitude of the stress tensor distribution and its gradient on and in the produced or used steel.

This technology apart from allowing for the knowledge of the stress tensor distribution can also be used for obtaining stress annihilation or control, by means of achieving the proper stress level either by stress relief or by stress accumulation process or by their combination. Stress relief is obtained by thermal and/or mechanical methods. Thermal annealing permits stress relief, while quenching (achieved by heating and consequent fast cooling) provide stress accumulation. Additionally, mechanical treatment can also provide stress annihilation or control. In all these treating methods, our stress monitoring method and instrument can serve as the feedback control of the automated system to precisely control stresses at any local point of the under test and treatment steel. The additional cost of this automated process system is only the mentioned new measuring system and the corresponding software feedback codes, since thermal (annealing & quenching) and mechanical treatment process is currently used in all modern steel production lines.

1. Introduction

The use of nondestructive methods for the determination of residual stresses has been of increasing interest over the last years [1]–[4].Magnetic non-destructive techniques use this coupling between the structural and magnetic configuration for testing and evaluating metallurgical, microstructural, mechanical and micro-magnetic features in ferromagnetic steels [5-8]. The standard methods used for the residual stresses monitoring in steels are the X-ray method with the Bragg - Brentano technique (XRDBB), which relates to two-dimensional stress monitoring technique (i.e. stresses distributed on the sample's surface) [9] and neutron diffraction method (ND) referring to three-dimensional monitoring of the stress tensor (measuring on the thickness of the material) [10]. These two methods are characterized as laboratory techniques, which require large infrastructure and time to achieve a point measurement. Lately, new portable X-ray diffraction devices which enable XRDBB method, appeared on the market. These set ups are suitable to carry out two-dimensional point identification of stresses, in samples whose surface has been prepared in accordance with the requirements set by the manufacturer and configures the measurement environment.

Anothermonitoring method involves the measurement of the Magnetic Barkhausen Noise (MBN). The method is based on the Barkhausen jumps during the magnetization procedure of a ferromagnetic steel caused by the development of a micro-stress-strain domain, which relates to overcoming imperfections – barriers such as grain boundaries, disorders forests, precipitations, structural defects. There are several studies based on this principle, some of which measure the stress field [11]. In some cases, this method is able to oversee the two-dimensional tensor of surface tension on the surface of the under test steel and surveillance of the spatial distribution of stresses it is also possible by moving the sensor. The MBN method and the sensors based on this method require the correct positioning of the sensor, since any deviation from this, introduces large geometric uncertainties and causes multiple changes in the output signal of the magnetic sensor.

2. Methodology

All these methods involve the measurement of surface square stresses, with the first two related t point-stress measurement, and not on the distribution of the surface tensor trends, while the third method relates to the measurement of the spatial distribution of the surface tensor trends alone. In any case, the three-dimensional distribution of the tensor of stresses can be significantly different from the two-dimensional distribution of the surface stress, for several reasons.

They have also been developed magnetic stress tensor monitoring techniques on the surface and bulk of the under study ferromagnetic steel, where the method, devices and sensors which are used relate to magnetic properties monitoring, meaning surface MBN and surface permeability, as well as an in depth magnetic permeability measurement of the steel [12]. This methodrelates to the monitoring of residual stresses (residual stresses) in steels having achieved uncertainty of better than 1%. The residual stresses are introduced into the steel by welding. Then, the methods XRDBB and ND are used for the inspection of residual stresses along the heat-affected zone and the melting zone. The limits of square stresses are within the elastic region, they do not exceed the mechanical yield strength, either tensile (positive) or compressive (negative) stresses. The subsequent monitoring of surface magnetic properties to the same sites where the stresses were measured with the use of surface magnetic permeability sensors or MBN sensors is associated with XRDBB measurements, giving a monotonic response across the spectrum of residual stresses with a deviation between the surface magnetic measurements and stresses to be better than 1%. Similarly, by monitoring the magnetic permeability tensor throughout the bulk of the material, on the same points where the neutron diffraction measurements are made a monotonic correlation between the bulk magnetic permeability and corresponding stresses components with an uncertainty of better than 1% is obtained. Thus, the MAgnetic Stress Calibration (MASC) curve is derived, ie for stresses below the yield point under tensile conditions or compressive stress, it is able to appreciate the quality of the welding of the steel or to determine its residual stresses using laminated cores as reference samples, as well as zero-stresses samples. These measurements relate to assay type stresses II (inter-grain stresses, i.e. measurements regarding the average tensor of stresses in neighboring granules of ferromagnetic steel, with overall diameter of the order of 1 mm). In this study, the the electron back scattering diffraction(EBSD) technique is used for monitoring type stresses III (intra-grain stresses, ie measurements of the average of the tensor of intragranularly stresses in total analyzed volume of the order of a few cubic microns), with a deviation between the surface magnetic permeability and EBSD estimation better than 3%.

However, the present under measurement steel may involve residual stresses (type II stresses and III) with or without an external hydraulic stress (type I stresses). The general case is that the hydraulic stress tensor (i.e., stress applied at the same way throughout the length of the under measurement steel) is algebraically added to the corresponding tensor of residual stresses, so that the overall stress value may possibly enter the plastic deformation range of the under measurement steel.

3. Results and Discussion

Fig. 1 illustrates the agreement between stress measurements across the weld on the surface (top two figures) and in the bulk (bottom two figures) of a steel weld (dot points) and magnetic permeability scan (continuous line).

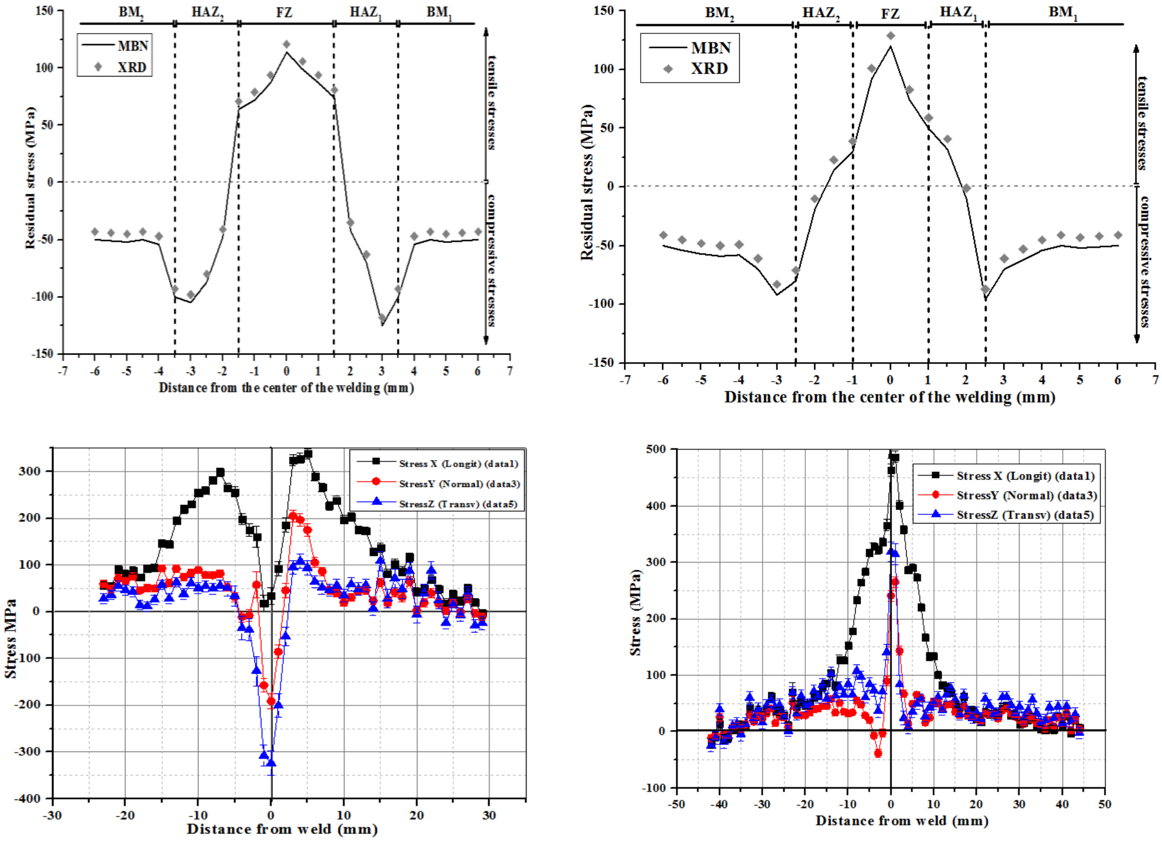

Fig.1:*Comparison of stresses and magnetic properties along welded zones: Top: comparison between XRD-BB determined surface stresses (bold dots) and magnetic surface permeability (continuous line). Bottom: Neutron diffraction based stress tensor determination compared with bulk permeability tensor (error in bulk permeability is much lower than the neutron diffraction uncertainty).*

Following this excellent agreement between magnetic permeability and stresses, had achieved the extraction of MASC and so is possible to determine the stress state in a given direction by the monotonous dependence of magnetic properties and stress of the MASC curve. Fig. 2 illustrates the MASC in different grade of steels.

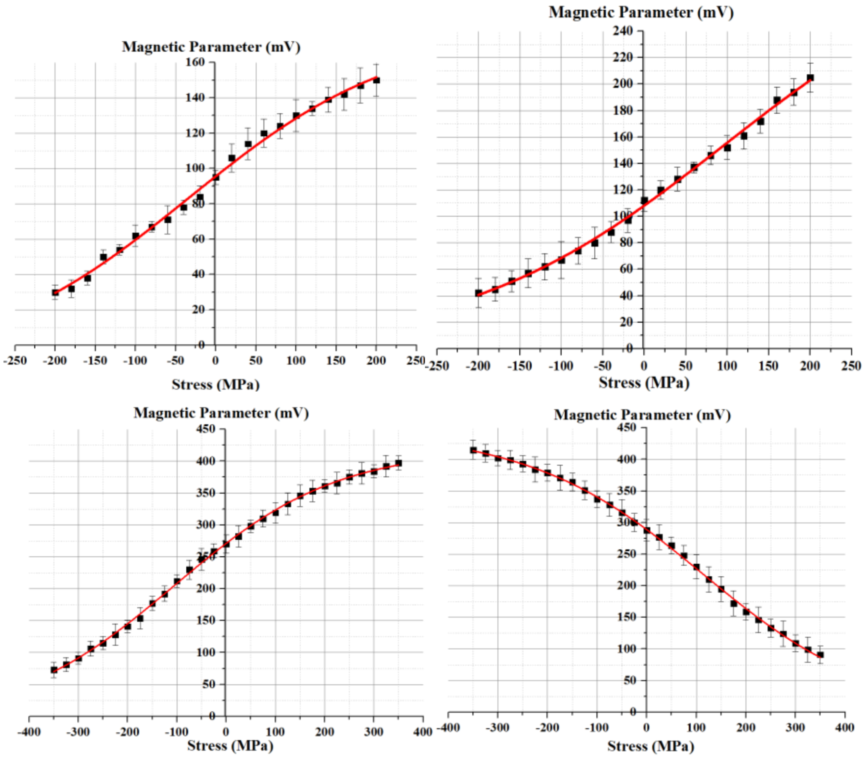

Fig. 2: *Magnetically calibrated stress dependence in different types of steels: top figures illustrate the performance of single phase electric steel (left) and AISI 1008 steel (right), while bottom figures illustrate the dependence of AISI 4130 steel (left) and Fe-Co micro-alloyed steel (right).*

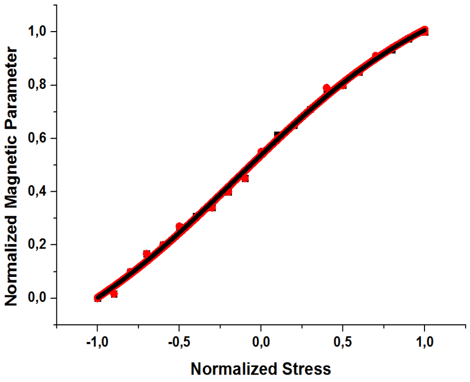

Fig. 3: *The universal MASC curve: measurement of two specific magnetic parameters permit the stress component along the direction of magnetic measurement.*

Furthermore, it has achieved a universal law on such stress-magnetization dependence according to which normalization of MASC with certain parameters and resulted in a unique universal MASC curve(Fig. 3). This way, there is no need to know the grade of the examined steel. The measurement of the mentioned magnetic parameters determines the stress component in the direction of measurement.

4. Conclusions

This technology, changing the map of non-destructive testing of steels, will allow for advanced steel production methods and procedures: those manufacturers who are to adopt this method will offer steel products with properly measured and obtained characteristics along the whole area and volume of the steel, governed by the corresponding stress distribution.

This technology can also be used in the steel manufacturing products such as pipeline manufacturers, steel tool manufacturers, as well as the users of these products, like energy (classic thermoelectric or hydroelectric stations, as well as nuclear stations), oil & gas applications, shipping, automotive industry, railway & train industry and construction.

The method is under standardization process in National, European, American and International Standardization Bodies; in parallel, the method is currently being adopted from certification bodies, ship classes, specific institutions etc. in the form of directives and procedures to be followed by steel manufacturers and users.

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