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Design of an expert system based on neuro-fuzzy inference analyzer for on-line microstructural characterization using magnetic NDT method

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A B S T R A C T

Tracing microstructural evolution has a significant importance and priority in manufacturing lines of dual-phase steels. In this paper, an artificial intelligence method is presented for on-line microstructural characterization of dual-phase steels. A new method for microstructure characterization based on the theory of magnetic Barkhausen noise nondestructive testing method is introduced using adaptive neuro-fuzzy inference system (ANFIS). In order to predict the accurate martensite volume fraction of dual-phase steels while eliminating the effect and interference of frequency on the magnetic Barkhausen noise outputs, the magnetic responses were fed into the ANFIS structure in terms of position, height and width of the Barkhausen profiles. The results showed that ANFIS approach has the potential to detect and characterize microstructural evolution while the considerable effect of the frequency on magnetic outputs is overlooked. In fact implementing multiple outputs simultaneously enables ANFIS to approach to the accurate results using only height, position and width of the magnetic Barkhausen noise peaks without knowing the value of the used frequency.

1. Introduction

Prediction of microstructural evolution is a topic of great importance in production lines of different steel components which engrossed the attention of researchers and also engineers. In order to put such a task into practice, many expensive and time consuming destructive evaluations including metallography, hardness measurement, mechanical testing etc. are involved in related ferrous industries. Therefore, there has been resurgence of interest for application of modern and cost-effective nondestructive testing.

Nowadays, there are large numbers of nondestructive testing techniques that have been introduced based on different physical principles. Among them, magnetic Barkhausen noise (MBN) has been widely used for nondestructive characterization for a variety of ferromagnetic materials under various conditions [1]. The MBN technique can be performed with magnetic sensors positioned locally on top of the surface of a sample, which enables the MBN for in-process measurement with the advantage of considerably short measuring time that is quite important in large continuous fabrication lines [2].

When a ferromagnetic material is subjected to an external time varying magnetic field, the nucleation, motion and annihilation of magnetic domain walls occurs which result in nucleation and growth of new magnetic domains. The MBN originates from discrete motion of magnetic domain walls overcoming various pinning sites like precipitates, grain boundaries, inclusions and dislocation pile-ups. This irreversible movement of magnetic domain walls is responsible for the production of a pulsating magnetization (a noise like signal) corresponding to the variation of magnetic flux [3–6]. Due to the sensitivity of MBN to microstructure, it is considered to be a promising and efficient candidate for determination of microstructural evolution in a wide range of engineering materials [7–12].

A typical utilization of the MBN includes extracting of certain features from the measured signal and comparing of this information with properties of studied material. In other words, the assembled system ought to only be calibrated on reference samples of known and recognized properties to predict the properties of unknown samples. Typical calculated features are the root mean

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square (RMS) [13] and the MBN energy [14] and a more recent approach, considers the peak height, width and position of the MBN profiles [15]. However, using the MBN measurement for quantitative prediction of material properties is a very challenging task due to complex and hard to achievement of interactions between material properties and the MBN outputs [16]. On the other hand, another important issue to be considered is finding the optimum magnetizing working frequency. The excitation frequency can be set to anywhere between 0.5 and 10 Hz and even much higher in specific cases [17]. Since the frequency of the output is rich in information, it can noteworthy affect the outputs and corresponding results which complicate the situation of nondestructive evaluation and later interpretation. Nevertheless, in order to increase the applicability of the MBN as a reliable nondestructive testing tool, it is essential to establish an accurate and reliable relationship between the features of the MBN signals measured by the sensor and the material desired microstructure. This may be achieved by means of many novel approaches like using artificial intelligence concepts in neural computation. Fulfilling this task, especially when the affecting parameters and their corresponding relationships are very complex and non-linear, a variety of useful soft computing techniques can be utilized. Among different soft computing methods, adaptive neuro-fuzzy inference system (ANFIS) which is an optimum knowledgeable combination of artificial neural networks and fuzzy logic has indicated good performance for high accuracy prediction of material properties in complex systems [18]. Fuzzy logic system was first introduced by Zadeh [19]. It is more in-line with human's interpretation and decision making system due to usage of linguistic phrases instead of numerical value used in ANN [20]. In fuzzy logic, every factor is defined by its membership description. Suppose X, x and $\mu_B(x)$ are, respectively, the universe of discourse, the element of the universe and its related membership function. Therefore, a typical fuzzy set (B) can be identified as Eq. (1) [21,22]:

$$B = \{(x,\ \mu_B(x)) | x \in X\} \tag{1}$$

Fuzzy logic is an inference system that explains the system behavior in the form of 'IF–THEN' rules using analyzer knowledge or available processed data of the system. The general form of a fuzzy IF–THEN rule is [22]

$$\text{Rule: If } x \text{ is } A; \text{ then } y = B \tag{2}$$

Advantage utilization of both neural networks and fuzzy logic model leads to implementation of ANFIS. ANFIS is some kind of fuzzy model in which a feed-forward neural network is used for the weighted value evaluation of rules. In other words, a feed-forward back-propagation algorithm determines the parameters of membership functions. Feed-forward back-propagation algorithm can learn and store mapping relations between input(s) and output without knowing and even trying to derive mathematical equations describing the mapping [23].

The ANFIS provides a process for the fuzzy modeling procedure to achieve information about a data set in order to shape and regulate an appropriate membership function that assists fuzzy logic rule inference engine in linking input(s) and output [24].

In the present paper the concept of a more robust artificial intelligence method is introduced to increase the applicability of the MBN as a reliable nondestructive testing tool. In this regard, a set of experimental data have been gathered to obtain the initial database used for training and testing the ANFIS. In the current research, dual-phase (DP) steels samples with different percentages of martensite hard phase have been chosen wisely to study the affectivity and efficiency of this new hybrid approach.

2. Materials and methods

The materials used in this study is DP steels which are being increasingly used by the automotive industries as a suitable alternative for conventional plain carbon steel components. The goal for using such steel categories is due to the need of advanced materials with an excellent combination of high strength, cost-effective and acceptable ductility. Relative weight reduction, economical fuel cutback and an improved safety are some of the beneficial applications of DP steels in automotive industries [25]. DP steels consists of microstructures entailing hard second phases (martensite) dispersed throughout the ductile matrix (ferrite) and their microstructures are analogous to a composite composed of a ferritic matrix reinforced by islands of martensite [26].

Samples (200 mm long × 20 mm width × 1.3 mm thickness) from cold-rolled low-carbon steel were intercritically annealed in furnace under several conditions [1,27] in order to produce different DP steels with various volume fractions of martensite i.e. 15, 17, 23, 28, 35, 37, 40, 45, 58, 89 and 100 vol%. The steel's composition was Fe–0.08C–0.41Mn–0.50Si–0.09P–0.23Ni–0.39Cr–0.32Cu (in wt%). As a typical view of microstructure arrangement, SEM micrograph shown in Fig. 1 illustrates a typical microstructure of the DP steel containing 40 vol% martensite (black and white regions represent ferrite and martensite, respectively).

The used equipment to measure and evaluate the MBN signals was multi-frequency, tailor-made device interfaced to a computer for data acquisition. Schematic layout of the experimental system is shown in Fig. 2. The MBN device consisted of a sinusoidal shaped current generator with a wide range of frequencies (0.5 Hz to 5 MHz), the amplifiers, a probe (consisting of excitation and pick-up coils) and an Analogue/Digital converter. The DP specimens were magnetized using a U-shape ferritic core clamped to the surface of specimens. The magnetization coil, 500 turns of 0.35 mm insulated copper wire around the ferritic core, was regulated by a sinusoidal current generator with the frequencies of 5, 6, 7 and 10 Hz. These frequencies were used in order to minimize the undesirable effect of eddy currents on the applied magnetic field and to ensure a relatively constant rate of magnetization in the DP steel specimens [28]. In addition, low frequencies can gather and record sufficient information from the volume of materials at greater depths instead of near surface magnetization according to the equation of electromagnetic skin depth [29]. The

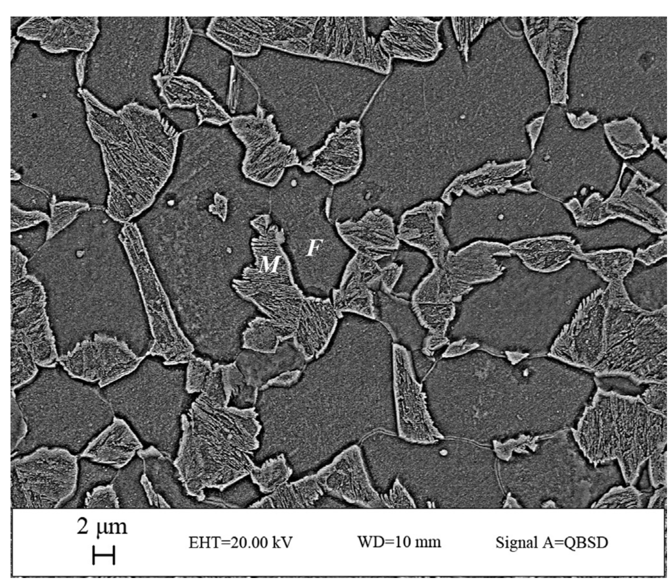

Fig. 1. SEM micrograph of the DP steel containing 40 vol% martensite. The ferrite and martensite are indicated with F and M, respectively.