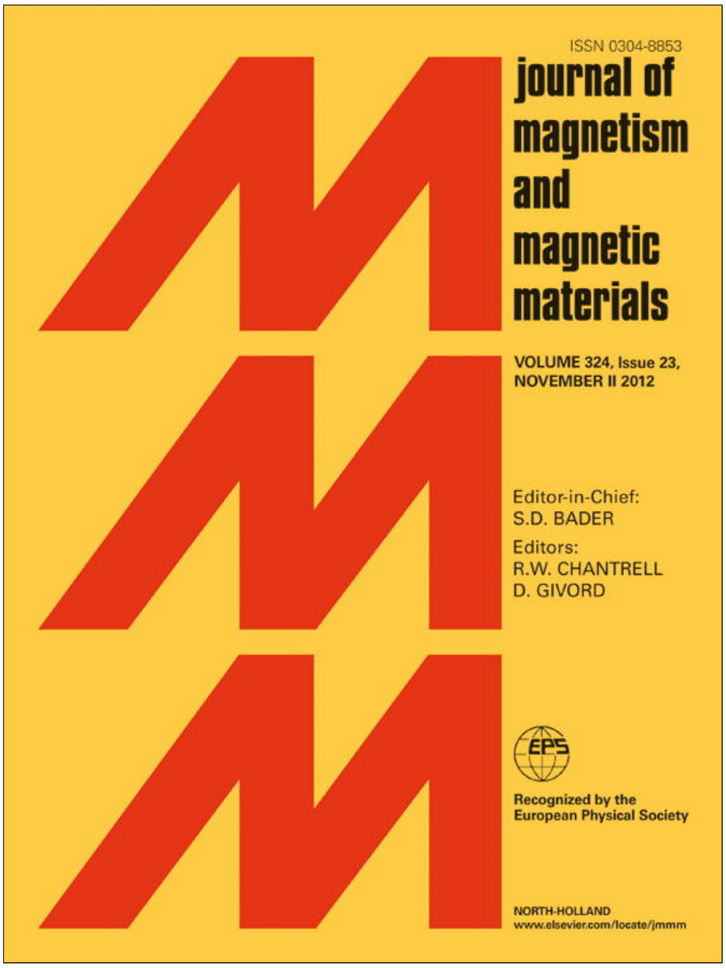
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Current Perspectives

Magnetic nondestructive technology for detection of tempered martensite embrittlement

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A nondestructive eddy current technique is used to evaluate tempered martensite embrittlement in 4340 AISI steels after quench and tempering in the range 240–550 °C. A relation between the responses of the magnetic induction (normalized impedance of the coil) and destructive Charpy impact test results has been established. The study shows that the eddy current method could be used to separate brittle parts due to the microstructure changes.

1. Introduction

In all heat treatment processes, there should be a balance between the properties of strength and ductility. In the tempering process, accurate control of time and temperature is critical to produce optimized microstructure and mechanical properties in the parts. It has been well recognized that ultrahigh strength alloy steels exhibit embrittlement when they are tempered in the temperature range 300–400 °C, which results in an obvious drop in impact strength. This phenomenon is an irreversible reduction in the toughness of steel due to a microstructural change and chemical effects which is called tempered martensite embrittlement (TME). The mechanism for tempered martensite embrittlement has been investigated by many investigators [1–3]. This form of embrittlement does not affect room-temperature tensile properties but causes significant reductions in impact toughness and fatigue performance.

From a practical point of view, determining and separating brittle samples in mass production of heat treated parts can be a key factor in quality inspection of the components. The traditional and widely accepted method for determining TME is performing the Charpy impact test. The destructive method is a standardized high strain-rate test which determines the amount of energy absorbed by a material during the fracture. It can, also, act as a tool to study temperature-dependent brittle–ductile transition. Disadvantages of this method are as follows: 1—scattering data, 2—time consuming preparation of the standard samples, 3—extensive dependence of the result on the v-notch preparation, and, 4—can only be used on a small fraction of samples in quality inspection process.

In the recent years, considering the advantages of nondestructive methods in quality control, several researches have been focused on nondestructive evaluation of microstructure of materials as a substitution for destructive methods. The new application of eddy current (EC) technique results in saving time and energy as well as providing 100% quality inspection in mass production lines [4,5].

There have been many researches to evaluate the microstructural changes using the EC nondestructive method. For instance, pearlite percentage of plain carbon steels and ductile cast irons [6–9], surface characterization of decarburized and carburized steels [10–13] as well as determining case depth of induction hardened steel rods [14] and the effect of mechanical microhardness on impedance variations [15] have been evaluated using the EC method. Despite the mentioned applications, the potential of the EC method to evaluate and determine the occurrence of TME has not been fully explored. In the present investigation, relations between EC output signals and microstructural changes in tempered 4340 steel have been established. The obtained relations, backed by SEM images as well as the Charpy impact test results, were used to detect TME in the steel samples.

2. Experimental procedure

The present research is conducted on six specimens of AISI 4340 alloy steel, the chemical composition of which is given in Table 1. This steel is known for its susceptibility for TME at the

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temperature range 300–400 °C. All samples used for destructive and EC tests were, first, normalized at 870 °C for 1 h to obtain the same homogeneous microstructures prior to hardening heat treatment. Then, the samples were austenitized for 1 h at 1050 °C and were oil-quenched to induce martensitic transformation and finally tempered in the range 240–550 °C to produce different tempered microstructures.

Considering inherent data scattering regarding the Charpy impact test, three samples were prepared for each specified tempering treatment. The impact tests were conducted according to ASTM A370 and the average values for each of these three samples were considered as destructive results to compare with nondestructive ones. The hardness of the quenched and tempered steels was also measured on Rockwell Hardness C scale (HRC). All the destructive results have been presented in Table 2.

Scanning electron microscopy images of fracture surfaces for specimens tempered at 240 °C, 380 °C and 550 °C were obtained using a TS 5136MM unit.

Finally, the EC tests were performed on the cylindrical samples (25 mm diameter and 150 mm length) at a frequency ranging from 5 to 100 Hz (in 5 Hz steps) and 5 Hz was chosen as an optimum operating frequency. A schematic diagram of the used EC system can be found elsewhere [12–14]. The EC test was applied using two different coils. The primary (excitation) coil of 500 turns is connected to an AC source and produces an alternating magnetic field surrounding the coil. The secondary (pickup) coil of 600 turns is used to analyze the EC responses and connected to an A/D Card. The EC test was performed at 27 °C with a fill factor of 98%. The responses of EC probe to the samples with different microstructures were studied using an impedance plane plotting of the real resistive impedance (R), versus the imaginary reactive impedance (ωL). Besides, the relation between normalized impedance (Z/Z_0) of the coil and the samples with various microstructures were also studied. EC outputs could be affected by partial variation in signal characteristics such as operating frequency and electrical current. To study reproducibility of the EC data, standard deviations of four measurements on each sample have been calculated and presented in Table 2.

3. Results and discussion

As Table 2 shows, the hardness of the samples cannot be used to separate the brittle samples. As a result, impact tests are traditionally used to detect the occurrence of TME. The results show a decrease in the energy of fracture for the samples tempered in the range between 340 °C and 380 °C.

It is well known that the response of EC signals is affected by microstructure and chemical composition of the sample. Indeed, any microstructure changes, due to the application of different heat treatment cycles, have a direct effect on electromagnetic properties of steel samples such as magnetic permeability, magnetic hysteresis curve parameters and magnetic Barkhausen noise [16–19]. Since the EC outputs are affected by these properties, it is possible that the response to eddy current induction is, indirectly, affected by microstructure changes providing a similar chemical composition. Fig. 1 visualizes this relation.

To present EC responses, impedance plane and movement of impedance point location, which are well theoretically established, have been used in many researches [20–22]. The impedance plane diagram can, also, be used to map the changes in EC coil impedance as a function of variations in the test sample microstructure. The details of the impedance plane calculations have been mentioned elsewhere [12,13,23]. The results of calculations for characterization of tempered microstructures are presented in Fig. 2.

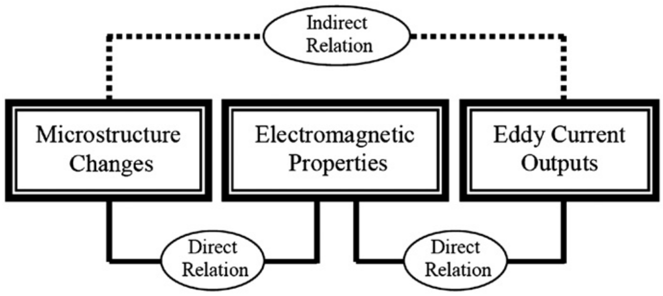

Fig. 1. Schematic relation between microstructure, electromagnetic properties and eddy current outputs.

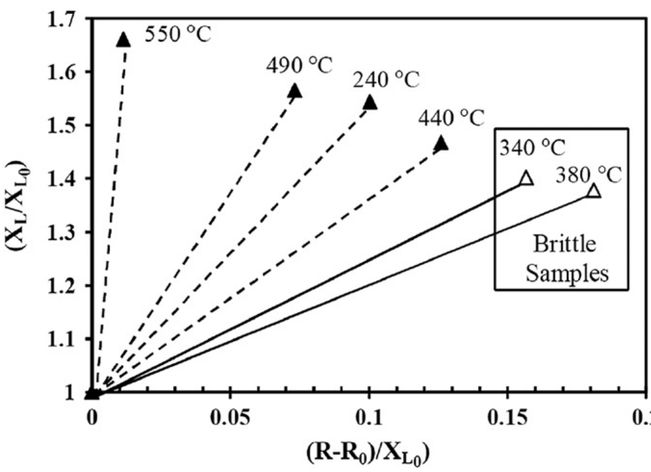

Fig. 2. Impedance plane and effect of tempering temperature on location of impedance point.

Table 1
Chemical composition in weight percentage.

Steel	C	Mn	Cr	Mo	Ni
AISI 4340	0.35	0.50	1.40	0.17	1.40

Table 2
Hardness, impact energy and EC measurements of tempered samples.

Tempering temperature (°C)	240	340	380	440	490	550
Hardness (HRC)	49.50	47.50	45.50	44.75	41.50	36.75
Impact energy (J)						
Sample 1	30.00	22.00	21.00	24.50	28.50	47.50
Sample 2	27.00	20.00	19.50	21.50	27.00	52.00
Sample 3	31.50	20.00	20.50	23.00	25.50	50.50
Average	29.50	20.67	20.34	23.00	27.00	50.00
Average normalized impedance $\pm$ standard deviation	1.043 ± 0.0031	1.005 ± 0.0033	1.005 ± 0.0031	1.021 ± 0.0029	1.043 ± 0.0034	1.065 ± 0.0029

As the results of impact test indicate, the 4340 steel exhibits minimum fracture energy in the tempering temperatures of 340 and 380 °C. SEM micrographs on the fracture surfaces of the samples (Fig. 3) reveal a fracture mode transition for samples tempered at 240, 380 and 550 °C. The fracture surface of the specimen tempered at 380 °C shows a partially intergranular fracture mixed with cleavages (Fig. 3b). Since, TME is attributed to the occurrence of intergranular and/or cleavage fracture, it can be concluded that TME has been occurred for this sample. However ductile fracture associated with micro void coalescence was predominately observed on the fracture surfaces of the specimens tempered at 240 and 550 °C (Fig. 3a and c).

TME is thought to be resulted from the combined effects of cementite precipitation on prior-austenite grain boundaries or inter-lath boundaries and the segregation of impurities at prior-austenite grain boundaries. A major cause for TME associated with cleavage fracture is the transformation of retained austenite at martensite lath boundaries to form coarse carbides [1–3]. The high density spherical carbides were observed for brittle samples in comparison with the other ones (the tempered samples at higher and lower temperatures) [24]. As a result of the cementite precipitation or segregation of impurities on austenite grain boundaries in the brittle steel samples, pinning of magnetic domain walls could happen during the application of the magnetic field. This leads to less mobility of magnetic domain walls in microstructure of the brittle samples. Thus, more magnetic field intensity (H) is required to overcome the obstacles against aligning the domains and more coercivity is needed. Therefore, in the brittle samples, the coercivity and hysteresis loss increase while the magnetic permeability (μ) decreases [16,24]. The mentioned differences in magnetic properties are the main reason for different responses of EC for samples with various microstructures. In other words, considering eq. (1), it can be concluded that decreasing in μ results in decreasing of self-induction coefficient (L):

$$L = \mu N^2 A/l \qquad (1)$$

where μ is the magnetic permeability, N is the number of turns around the coil, A is the cross section area and l is the coil length. According to Eq. (2), by the decrease in magnetic permeability (μ), induction resistance (X_L) is decreased:

$$X_L = 2\pi f L \qquad (2)$$

Besides, carbide precipitation in grain boundaries causes an increase in the resistance. Therefore, lower X_L and higher R could be achieved for brittle samples, which are shown in Fig. 2.

As a result, according to Eq. (3), the impedance of the coil will be the least for brittle samples as shown in Fig. 4:

$$Z = \sqrt{X_L^2 + R^2} = V/I \qquad (3)$$

Fig. 4 demonstrates variation of normalized impedance versus tempering. As it can be seen, there is a good correlation between the two sets of results (destructive impact test and nondestructive EC one). In both graphs, an expected drop for brittle samples is presented, which suggests the accuracy of nondestructive EC

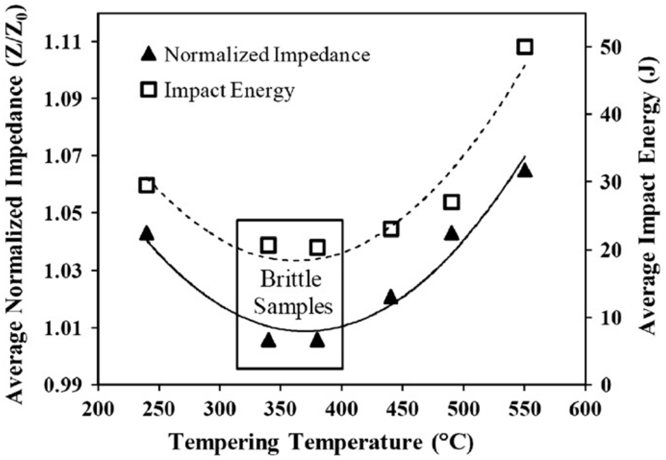

Fig. 4. Impact energy and normalized impedance versus tempering temperature of the samples.

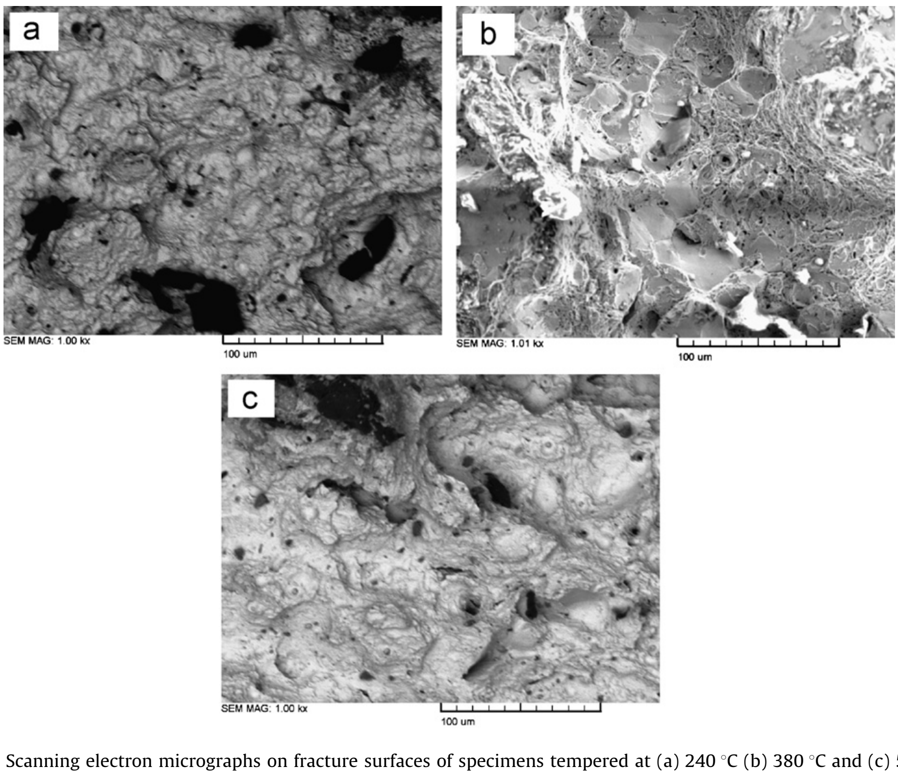

Fig. 3. Scanning electron micrographs on fracture surfaces of specimens tempered at (a) 240 °C (b) 380 °C and (c) 550 °C.

technique in distinguishing the brittle samples due to their difference in microstructure and magnetic properties with the other ones.

4. Conclusion

The EC signals could be employed efficiently for determination of micro-structural properties of high strength 4340 tempered steel. Normalized impedance changes as a function of tempering temperature and drops for samples with TME. The results of EC nondestructive method to distinguish the brittle samples represent a comparable accuracy to the destructive Charpy impact test.

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