Determination of Tempered Martensite Embrittlement using Eddy Current method

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Abstract :

After tempering of steel parts in the range of 260°C to 400°C there is a risk of Tempered Martensite Embrittlement (TME). The common method for determining embrittlement is the destructive impact test which is expensive and time consuming and control of all products is not possible by this method. In the recent years, the destructive methods are widely replaced by the nondestructive methods considering the capabilities and advantages of these methods in quality inspection of industrial products. In the present research 4340 AISI steel bars have been quenched and tempered in the range of 240°C to 550°C. Then Charpy impact test is applied on all the prepared samples. Finally determining the optimum frequency, nondestructive eddy current testing was applied for all samples and the responses to electro-magnetic field such as primary and secondary voltages as well as normalized impedance have been established. The study shows Eddy Current method could be successfully used to distinguish and separate brittle parts due to the microstructure changes.

Keywords :

Tempered martensite embrittlement, normalized impedance, eddy current method

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After tempering of steel parts in the range of 260°C to 400°C there is a risk of Tempered Martensite Embrittlement (TME). The common method for determining embrittlement is the destructive impact test which is expensive and time consuming and control of all products is not possible by this method.

In the recent years, the destructive methods are widely replaced by the nondestructive methods considering the capabilities and advantages of these methods in quality inspection of industrial products. In the present research 4340 AISI steel bars have been quenched and tempered in the range of 240°C to 550°C. Then Charpy impact test is applied on all the prepared samples.

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1. Introduction

When carbon alloy steels are tempered over the temperature interval of 250-400ºC (480-750ºF), an obvious drop in impact strength is observed. This phenomenon is a reduction in the normal toughness of steel due to a microstructural change and chemical effects which is called Tempered Martensite Embrittlement (TME).

TME is an irreversible phenomenon which occurs in certain quenched and tempered steels and even in ductile irons with susceptible compositions. This form of embrittlement does not affect room-temperature tensile properties but causes significant reductions in impact toughness and fatigue performance [1].

From practical point of view, determining and separating of brittle samples in mass production of heat treated parts can be a key factor in quality inspection of components.

The conversional method for determining TME, which widely applied in industry, is Charpy impact test. This destructive method, also known as the Charpy v-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture. This absorbed energy is measuring given material's toughness and acts as a tool to study temperature-dependent brittle-ductile transition.

Disadvantages of this method are: 1- scattering data, 2- preparation of the standard samples is time consuming, 3- obtained result is extremely depend on v-notch situation 4- can be used on a small fraction of samples in quality inspection process.

In the recent years, considering the disadvantages of destructive methods and advantages of non-destructive ones in quality control, several research have been focused on non-destructive determination of the

mechanical and micro-structural properties of materials as a substitution for destructive methods. This new application for traditional eddy current techniques results in saving time and energy as well as providing 100% quality control in mass production line [2].
On the base of magnetic properties changes, there is a strong potential for research on the new applications for the nondestructive Eddy Current (EC) method. Sensitivity of this method to chemical composition, microstructure and residual stress makes it a reliable alternative to the conventional destructive methods such as metallographic and mechanical tests [3, 4].
There have been many researches to evaluate the microstructure changes using this nondestructive method. For instance, pearlite percentage of plain carbon steels and ductile cast irons [5, 6], surface carbon content of carburized steels [7], case depth of case hardened steel rods [8] and the effect of mechanical micro-hardness on impedance variations [9] have been evaluated using eddy current nondestructive method. Furthermore, evaluation of decarburizing depth of steels with a martensitic base microstructure has been investigated using harmonic analysis [10]. Among all the investigations by EC method there is a potential to evaluate and determine brittle samples resulting of tempering in a range of 250-400ºC. Therefore in the present paper in order to determine brittle samples, the relations of tempered samples with EC outputs have been studied.

2- MATERIALS AND METHODS

The present investigation is conducted on six specimens of AISI 4340 steel which chemical composition is given in Table 1. This steel is known for its susceptibility for TME at the temperature range of 250-400ºC.
Specimens of 25mm diameter and 150mm length were prepared for quench and tempering treatment at various temperatures. All the samples were normalized at 870 ºC for an hour to obtain same homogeneous microstructure. Then the samples have been austenitized at 1050°C and were oil-quenched to induce martensitic transformation and finally tempered in the range of 240°C to 550°C to produce different tempered microstructures.

TABLE 1: CHEMICAL COMPOSITION IN WEIGHT PERCENTAGE

Steel	% C	% Mn	% Cr	% Mo	% Ni
AISI 4340	0.35	0.5	1.4	0.17	1.4

According to ASTM A370, the standard specimen size for Charpy impact test is 10mm×10mm×55mm. Thus the specimens with these dimensions were prepared and the Charpy impact test is applied on them.
Finally, the Eddy Current tests were performed on the cylindrical samples at different frequencies. A schematic diagram of the used Eddy Current system is shown in Fig. 1. The Eddy Current testing was performed at 27˚C with the fill factor of 98%. A sinusoidal current was applied to the coil for all samples, output voltages (V) and input currents (I) were measured and the impedance (Z) of the coil was calculated using equation (1).

$$V = Z / I \qquad (1)$$

Calculated impedances of samples were divided by the impedance of the empty coil (Z_0) to make a new parameter called normalized impedance (Z/Z_0) [2, 3].

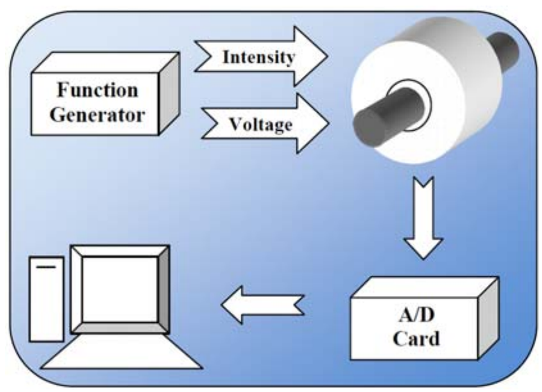

Figure 1: General synopsis of the experimental apparatus.

3- RESULTS AND DISUSSION

It is well known that the response of Eddy Current testing is affected by microstructure and chemical composition of the sample [2]. Indeed any microstructure changes due to the different heat treatments have a direct effect on electromagnetic properties of the steel samples such as magnetic permeability, magnetic hysteresis curve parameters and electrical conductivity. Since the eddy current outputs are affected by these properties, it is possible that the response of Eddy Current testing is indirectly affected by microstructures that provided from a similar chemical composition. Figure 2 describes these relations.

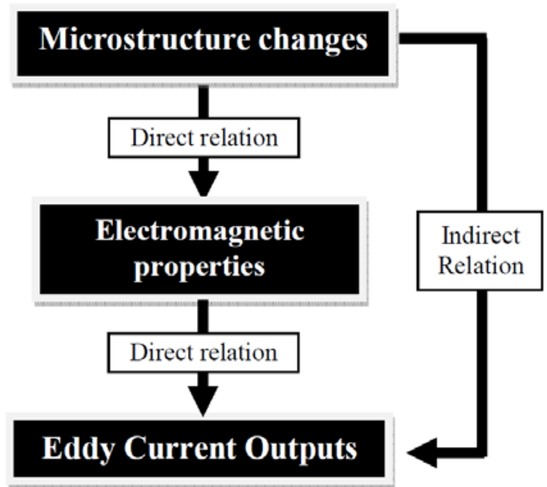

Figure 2: Schematic relation between microstructure, electromagnetic properties and eddy current outputs.

Tempering the samples in the temperature range of 240-550°C, TME is occurred on some samples. As it can be seen in fig. 3, hardness test as well as microscopic observation of the samples cannot be able to separate brittle samples.
Therefore in order to determine these samples, only Charpy impact test should be done. The results of this destructive test as it is shown in fig. 4, demonstrate an unexpected drop for impact energy of some samples. Indeed this test has been proved that TME has been occurred for tempered samples at 340, 380 and 440°C.

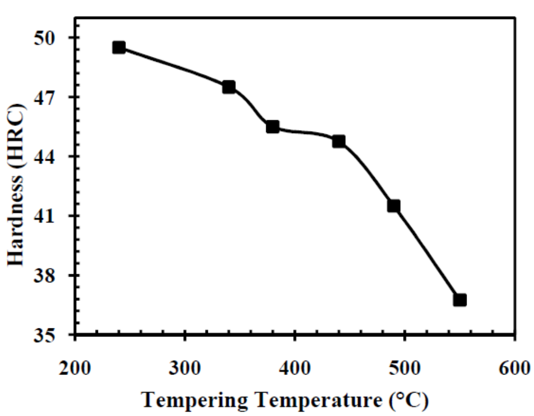

Figure 3: Hardness changes as a function of tempering temperature.

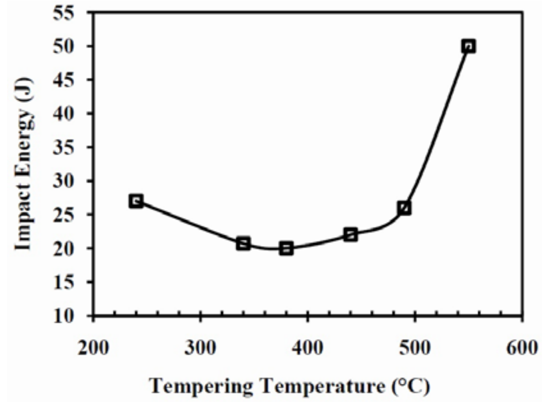

Figure 4: impact energy versus tempering temperature of the samples.

Tempered martensite embrittlement is thought to result 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.
To perform eddy current tests, the test frequency was altered from 1 to 100 Hz. Since the most significance difference between the outputs was obtained at the frequency of 5 Hz for normalized impedance, thus 5 Hz was chosen as an optimum frequency.
In Fig. 5 variation of normalized impedance versus tempering temperature at the optimum frequency is shown. As it can be seen there is a good correspondence between two obtained graphs by destructive impact test and nondestructive eddy current one as a function of tempering temperature. In the other word eddy current method can distinguish the brittle parts as well as the charpy impact test due to difference of magnetic properties of these samples with the other ones.
As a result of cementite precipitation or segregation of impurities on austenite grain boundaries in the brittle steel samples, pinning of magnetic domain walls have been occurred by applying magnetic field. This leads to less mobility of magnetic domain walls in microstructure of the brittle samples in comparison with the other samples. Thus more magnetic field intensity (H) is required to overcome the obstacles against aligning the domains and thus more coercivity is needed. Therefore in the brittle samples, coercivity and hysteresis loss increase and magnetic permeability (μ) decreases. The mentioned differences in magnetic properties are the main reason for the different responses of eddy

current for samples with various microstructures.

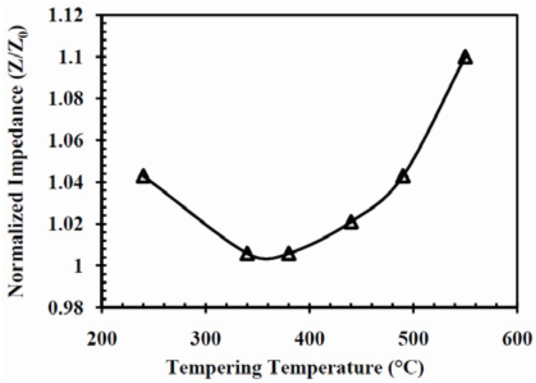

Figure 5: eddy current output (normalized impedance) versus tempering temperature.

In other word, considering (2), it can be concluded that decreasing in μ results in decreasing of self-induction coefficient (L).

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

Where μ is magnetic permeability; N is number of turns round the coil; A is cross section area and l is the coil length.

Therefore, according to (3), by decreasing in magnetic permeability (μ), induction resistance (X_l) is decreased. Since in ferromagnetic alloys (such as steel) the effect of permeability or reactance is stronger than the effect of resistance (R), impedance (Z) is decreased too (4).

$$X_l = 2\pi f L \qquad (3)$$

$$Z = \sqrt{X_l^2 + R^2} = V / I \qquad (4)$$

According to (4), the impedance decreases for brittle samples in comparison with the other samples (fig. 5).

4-CONCLUSIONS

The eddy current signals could be employed efficiently for the determination of micro-structural properties of steel samples. The results of this non-destructive testing method for distinguish the brittle samples represent a comparable accuracy to destructive testing method (charpy impact test).

According to the difference in magnetic properties of brittle sample's microstructures (Tempered Martensite Embrittlement), normalized impedance changes as a function of tempering temperature shows unexpected drops, i.e. corresponding to the brittle samples.

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