ABSTRACT

Magnetic NDE is one of the most suitable methods for the degradation of nuclear pressure vessels, since the magnetic properties are sensitive to lattice defects such as dislocations and Cu precipitates. Magnetic structure sensitive properties, coercive force, Rayleigh constant, initial susceptibility and the saturation susceptibility have been studied theoretically and experimentally and they have a simple relation with the dislocation density. Rayleigh constant, initial susceptibility and the saturation susceptibility are technically difficult to be measured in the opened samples. Coercive force would be suitable for the application to NDE from the view point of the measuring technique. But coercive force is less sensitive than the other properties. The ideal NDE properties should be sensitive to lattice defects and have a simple relation with them. We have the other properties due to Barkhausen noise effect, minor hysteresis loops and magneto acoustic emission. Their relation with dislocations has not been theoretically and experimentally studied fully and they do not necessary have a simple relation with lattice defects such as remanence. We need the standardization of magnetic properties for the NDE application at present. The magnetic properties for NDE should change consistently with coercive force. We shall introduce the standardization method for magnetic NDE for degradation in ferromagnetic steels with a few examples.

INTRODUCTION

The previous NDE in metal and alloys is for the observation of cracking by eddy current, supersonic wave and X-ray techniques. Of our interest is NDE of degradation before the crack initiation by magnetic methods; magnetic properties are very sensitive to lattice defects, especially dislocations and they can be obtained non-destructively. This magnetic method is available to NDE of the pressure vessels of nuclear reactors.

We have several magnetic properties sensitive to lattice defects in ferromagnetic materials such as low carbon steels. The relation of magnetic properties and dislocations has been studied theoretically and experimentally by Stuttgart group in Max-Planck Institute since 1950 [1-2]. Initial susceptibility, coercive force, Rayleigh constant and susceptibility approaching to saturation have a simple function of the dislocation density. But, these properties except for coercive force are difficult to use for NDE because of the measuring technique. The difficulty in the measurement of these properties is caused of the demagnetization effects. The other predominant properties are of Barkhausen noise effect. They are more sensitive than coercive force and possible of the measurement to objects with arbitrary shape. The properties due to Barkhausen noise effect, however, depend on the measuring condition.

We discovered seven magnetic properties of late that have advantaged characteristics to NDE; they are more sensitive to lattice defects than coercive force and they can be obtained by much lower magnetic field than the magnetic hysteresis loop [3]. We need the outer evaluation against new properties for the standardization.

The purpose of the present study is the evaluation of the magnetic properties as well as the measuring technique for NDE, i.e. the standardization of magnetic NDE. We have started Round Robin Test in Universal Network for Magnetic NDE [4] for the standardization of magnetic NDE. In this paper the standardization process is introduced taking an example by minor loop properties that were found by us.
STANDARDIZATION

Round Robin Test helps us to know several issues for the standardization of magnetic NDE. Some properties obtained from hysteresis loops show a good agreement with each other in the closed samples. In opened samples, however, we could not have good agreement in our results. The results by Barkhausen noise effect showed a large disagreement among each group.

The disagreement is an unexpected result for us, since these magnetic properties are caused of the interaction between magnetic domain walls and the lattice defects such as dislocations. The magnetic domain wall is a sensor in the magnetic NDE method. All the properties should change consistently with lattice defects. But our data do not necessarily agree consistently with each other. It is difficult to say which results are correct or wrong for the different results. But we have to judge our results, for the standardization of magnetic technique.

As Stuttgart group in Max-Planck Institute says, coercive force, the initial susceptibility and Rayleigh constant have a simple function of the dislocation density $\rho$ [1-2].

\[
H_c \propto \rho^{1/2}, \quad (1)
\]
\[
\chi_\text{0} \propto \rho^{-1/2}, \quad (2)
\]
\[
\alpha \propto \rho^{-1}, \quad (3)
\]

where

\[
B = \chi_\text{0} H + \alpha H^2. \quad (4)
\]

The relation represents the pinning effect of dislocations. We have a lot of data supporting the theoretical relation.

Coercive force is a reliable magnetic property experimentally and theoretically and possible to be obtained independent of the demagnetization effect. The reliable measurement for coercive force is possible for the closed samples as well as the open samples. It was measured in the Round Robin Test by several groups. The values of coercive force are nearly the same in the closed samples but different in open samples. The difference is caused of the measuring technique. The measuring technique should be improved in the open samples comparing with the closed ones. Coercive force is not disturbed by the demagnetization effect and the values of open samples should agree with the closed ones.
We have the other magnetic properties but for “coercive force”. These magnetic properties should agree with “coercive force” in their trend fundamentally. Absolute values are difficult to be obtained in some properties. But the trend of the relative ones should agree with “coercive force”. In the properties obtained from hysteresis loops, the values in closed samples are reliable compared with open samples. If some property disagrees with “coercive force”, we should explain the disagreement from the physical point of view.

We can indicate the fundamental precepts for the standardization of NDE as follows, i.e.

1. Coercive force obtained by use of the closed sample is a standard property.
2. The other properties obtained in the closed samples should be consistent with the coercive force.
3. The magnetic properties obtained in the open sample should agree with the values obtained by the closed samples.

“Remanence” is a magnetic structure sensitive property and shows a simple relation with coercive force but does not consistent with it (see Fig. 1). The values obtained by us agree with each other in the closed samples in the Round Robin Test. The relation between “remanence” and dislocations is not simple and its value is decided by the other factors, such as the demagnetization effect. We can say that “remanence” is not an appropriate property to get the information about lattice defects.

We have many magnetic structure sensitive properties. Some of them are not appropriate to NDE from two causes mainly. One is caused of the same reason as “remanence”. The other is caused of the measuring technique. The later would be conquered by the improvement of our technique. We should assign the reason for the disagreement of our data, due to the first reason or the second.

MINOR-LOOP PROPERTIES

Recently, we found several scaling rules of minor hysteresis loops which are independent of magnetic field amplitude as well as magnetic field [3,5-7]. The rules include

\[ W_F = W_F^0 \left( \frac{M_s}{M_u} \right)^n \]  

(5)
\[ W_R^* = W_R^\alpha \left( \frac{M_R^*}{M_R} \right)^{n_R}, \quad (6) \]
\[ W_a^* = W_a^\alpha \left( \frac{M_a^*}{M_a} \right)^{n_a}, \quad (7) \]

and

\[ H_c^* = H_c^\alpha \left( \frac{M_R^*}{M_R} \right)^{n_c}. \quad (8) \]

Here \( W_F^*, W_R^*, W_a^*, H_c^* \) and \( M_R^* \) represent the minor-loop hysteresis loss, minor-loop remanence work, minor-loop stored energy, minor-loop coercive force, and minor-loop remanence, respectively, as denoted in Fig. 2. The parameters depend on microstructures as well as the magnetic field amplitude \( H_a \). \( W_F^*, W_R^*, W_a^*, \) and \( H_c^* \) are the minor-loop coefficients sensitive to lattice defects. \( n_F, n_R, n_a, \) and \( n_c \) are constant independent of lattice defects and kinds of materials in Fe metal, its alloys and Ni metal; \( n_F = n_R = 3/2, n_a = 1 \) and \( n_c = 0.45 \). \( M_s \) and \( M_R \) are saturation magnetization and remanence.
respectively. Note that the power-law relation between $W_F^*$ and $M_a^*$ with $n_F = 1.6$ was discovered by Steinmetz about one century ago. It is well known as Steinmetz law [8].

The coefficients $W_F^o$, $W_R^o$, $H_c^o$, and $M_R^o$ reflect the interaction between magnetic domain walls and lattice defects, as well as the domain wall mobility. We studied the relation between coefficients with dislocations [5] and the irradiation defects [6] and found that the coefficients show the same relations with coercive force of the major loop. We studied the temperature dependence of the coefficients in the wide range between 10 K and 600 K in Fe and Ni metals and found that they have the same temperature dependence as coercive force [7].

**ROUND ROBIN TEST IN UNIVERSAL NETWORK FOR MAGNETIC NDE**

We started Round Robin Test among UNMNDE members for the standardization of magnetic NDE and have valuable data now. We have consistent results and inconsistent ones. I believe the first Round Robin Test is successful and fruitful. The second Round Robin Test has started on January 2009. We discussed our results in the UNMNDE 2008 meeting of Budapest. Our results were summarized standing on the base of our discussion and a report on Round Robin Test has been made. The data were obtained by

![Figure 4 - Minor-loop properties $W_F^o$, $W_R^o$, $H_c^o$ and remanence $M_R$ versus coercive force $H_c$ in cold-rolled low carbon steel. The sample is plate shape (40 mm×60 mm×10 mm).](image)
each member and belong to him. The data of Takahashi group are possible to be opened and are evaluated on the basis of the present precept of standardization. Minor-loop properties $W_F^\circ$, $W_R^\circ$, and $H_c^\circ$ are independent of the applied magnetic field as well as the amplitude of minor loops. Their change against dislocations agrees with that of coercive force in the closed samples as well as the open ones (see Figs. 1, 3 and 4). Here, the dislocations are introduced by cold rolling. Their sensitivity is higher than that of coercive force. Cu precipitates were induced by aging after 10% strain instead of neutron radiation. Cu precipitates grow up in size and density and gather around dislocations, where the stress field of dislocations compensates that of Cu precipitate. The magnetic properties increase, take a maximum and decrease with the growth of Cu precipitates. The minor-loop properties change consistent with coercive force in Fe-Cu alloy with 10% pre-strain (Figs. 5 and 6). The reliability for measuring values should be higher in the ring samples than Charpy impact ones and the measuring techniques for open samples have to be improved in our group.

Figure 5 - Minor-loop properties $W_F^\circ$, $W_R^\circ$, and $H_c^\circ$ versus coercive force $H_c$ in Fe-Cu alloy with 10% pre-strain. The sample is ring shape.

Figure 6 - Minor-loop properties $W_F^\circ$, $W_R^\circ$, and $H_c^\circ$ versus coercive force $H_c$ in Fe-Cu alloy with 10% pre-strain. The samples are Charpy impact test pieces.
REFERENCES


4) http://www.ndesrc.eng.iwate-u.ac.jp/UniversalNetwork/


