Electromagnetic Nondestructive Evaluation of Fusion Reactor First Wall

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Abstract

This research presented on the electromagnetic nondestructive evaluation of the degradation of structural steel materials in the nuclear industry, beginning with the establishment of ferromagnetic nondestructive test, covering the physical background, damage modes, measurement results of heat treated and fatigued A533B low alloy steel, the field calculation model for numerical analysis and a developed approach by Wavelet-Galerkin method.

1. Introduction

In this research the electromagnetic nondestructive evaluation method is proposed and applied to $A533B$ low alloy steel, in particular, which is the typical material of nuclear reactor pressure vessel. The goal is to determine the level of degradation in the microstructural and/or the mechanical properties changes which are essential from the view point of structural integrity. A great effort has been done in order to establish a systematic system of the electromagnetic methods for NDE.

2. Magnetic Property Assessment of Heat Treated $A533B$ Low Alloy Steel

Toroidal shape specimens were manufactured with outer diameter $26mm$, inner diameter $18mm$ and with $4mm$ thickness from $A533B$ material. The specimens were water quenched and tempered at three different temperatures $(620^oC, 650^oC, 680^oC)$.

A new measurement was proposed based on force between the specimen and the excitation field. To perform the force measurement in a simple way, a small cylindrical permanent magnet (SmCo) was used in order to produce excitation instead of an electromagnet. The acting force between the heat treated specimens and the permanent magnet was measured up to $2N$ with a $10^{-4}N$ accuracy as a function of the distance between them in order to make difference between the $A533B$ specimens heat treated in different way.

The result of the force measurement is in good agreement with the BH-curve measurement. The differences in the force curves due to the different tempering processes are depicted in Fig.1. They show systematic changes depending on the aging temperature. In the case of strong magnetic field there is no difference between the force curves. However in the case of weak fields, going toward the coercivity point of the hysteresis curve, the magnetization strongly depends on the mobility of magnetic domain walls, which is determined by the dislocation density, the aglomerates of point defects and the precipitation. The movement of the domain walls is much more difficult if there are more defects. Hence the larger observed force amplitude in the case of lower tempering temperature $(A533B - 620$ specimen), when less defect is recovered.

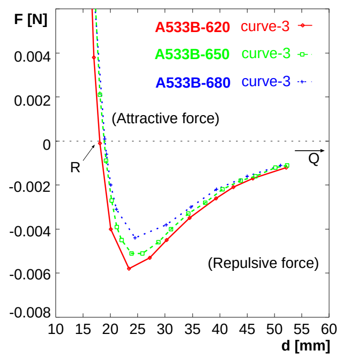

Fig. 1 : Variation of the force with different tempering temperatures

3. Evaluation of Fatigue Damage Based on the Magnetic Properties Measurement in $A533B$ Low Alloy Steel

Zero-tension fatigue test was conducted on a $50kN$ servo hydraulic system. The specimens were subjected to high cycle fatigue below the yield stress $(\sigma_y = 560MPa)$.

Load control was applied with sinusoidal waveform at a series of constant load amplitudes ($538MPa, 542MPa, 546MPa$). The frequency of the fatigue cycling was $2Hz$. For magnetic measurements the fatigue test was interrupted. The $A533B$ specimens were magnetized and the average value of the flux density (B_{AVG}) was picked up by a search coil wound around the specimen and the tangential component of the magnetic field (H_t) was measured by the Hall sensor of a Gauss meter attached parallel to the surface.

The results of the succesive magnetic measurements showed that:

i) The fatigue induced degradation in the microstructure mainly perturbs the upper part of the hysteresis curve, where magnetic domain rotation is more significant.

ii) Also the remanent induction decreases with fatigue cycling. This is plotted in Fig.2. for specimen fatigued at $538MPa$ maximum stress level.

iii) The coercive field did not show significant change, even if the TEM observation showed increasing dislocation density in the ferrite phase. The negligible change was in agreement with the negative result of the Vickers Hardness measurement.

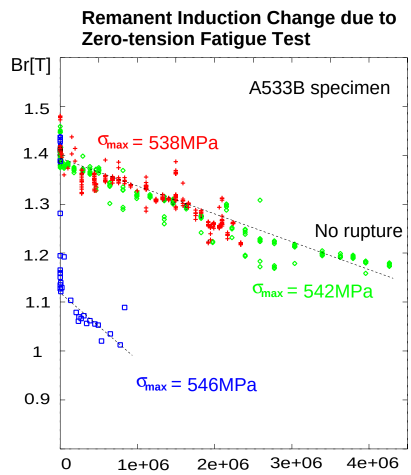

Fig. 2 : Remanent induction vs. number of fatigue cycles

For the interpretation of the magnetic properties change, the dislocation density increase in the ferrite phase, the degradation of martensite due to fatigue and the carbide precipitation have to be considered.

4. Conclusion

1) The magnetic and mechanical hardness are well correlated since the coercivity showed a linear dependence with Vickers hardness in the case of heat treated $A533B$ material.

2) The force measurement is very sensitive to magnetic properties changes even in the case of open magnetic loop as well. It shows clear and systematic differences for different specimens also in the case of a very weak applied field.

3) The magnetic nondestructive technique was succesfully applied to detect the changes in microstructure, caused by high cycle fatigue. The method was sensitive even at stress level below the yield stress. By TEM observations the increase of the dislocation density in ferrite phase and the division of the carbide precipitation due to the cyclic load were identified. These microstructural changes are translated into the shape modification of the upper part of the hysteresis curve and in the strong decrease of the remanent induction. The degradation of martensite phase is also a determining factor.

4) A new Wavelet-Galerkin method was developed, which is promising for NDE applications because of the orthogonality, compact support and multi-level structure of wavelet basis.