17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Relation between Magnetism and Charpy Impact Properties in Thermally Aged Fe–Cu Model Alloys

Yasuhiro KAMADA, Yousuke TOZAWA, Yuji SATO, Hiroaki KIKUCHI, Satoru KOBAYASHI, Katsuyuki ARA, Junichi ECHIGOYA, and Seiki TAKAHASHI

NDE & Science Research Center, Faculty of Engineering, Iwate University

Ueda 4-3-5, Morioka, 020-8551, Japan

Tel&Fax: +81-19-621-6431

E-mail: kamada@iwate-u.ac.jp. Web: http://www.ndesrc.eng.iwate-u.ac.jp/

Abstract

The objective of this study is to investigate the correlation between magnetic properties and the degree of embrittlement in thermally aged Fe–Cu alloys, with and without pre-deformation, which are the model specimens simulated for the irradiation embrittlement of nuclear reactor pressure vessel steels. With increasing aging time, the ductile-brittle transition temperature of both specimens increased due to Cu precipitation. On the other hand, the coercive field of as-quenched specimens increased, whereas that of pre-deformed specimens decreased under thermal aging. These results suggest the importance of the role of initial dislocation density for understanding the magnetic characteristics of irradiated steels.

Keywords: irradiation embrittlement, reactor pressure vessel, magnetism, dislocation

1. Introduction

Aging degradation of structural components used in nuclear power plants is becoming an increasing concern. The Charpy impact test—a destructive evaluation technique—is presently used for inspection of the irradiation embrittlement of reactor pressure vessel (RPV) steels. Since the surveillance test pieces were installed inside the reactor before the initial plant operation, the quantities of test pieces are restricted. The lifetime of existing nuclear power plants is now being extended for economic reasons, which will lead to a shortage of test pieces. Magnetic hysteresis measurement—a nondestructive evaluation (NDE) technique—is a promising candidate as an alternative inspection technique because of its high sensitivity to various types of lattice defects. Actually, a good correlation between the coercive field (H_c) and the ductile–brittle transition temperature (DBTT) has been observed for cold-rolled steels [1][2]. In this study, Fe–Cu alloys containing Cu precipitates, simulated for the irradiated microstructure of RPV steels, were

prepared and the correlation between H_c and DBTT was investigated.

2. Experimental Procedure

Fe–1.0wt%Cu model alloys were solution annealed at 1023K for 5h and specimens of Cu supersaturated solid solution were prepared. Half of the specimens were cold-rolled with a cold-rolling ratio (CR) of 10% in order to clarify the effect of initial dislocation density. Three types of specimen were cut from the plates: disk specimens (ϕ 3, t 0.1 mm), half-size Charpy V-notch specimens (w 10, t 5, l 55 mm), and ring-shaped specimens (OD 18, ID 12, t 2 mm). These specimens were thermally aged at 773K for 50 and 500min. Using the disk specimens, the precipitation behavior was directly observed by transmission electron microscopy. The Charpy impact test was performed at temperatures ranging from 170 to 400K. Magnetic *B*–*H* hysteresis curves were measured at room temperature by using the ring-shaped specimens with wound exciting and detecting coils, and the H_c of each specimen was obtained. The micro-Vickers hardness was also measured.

3. Results and Discussion

TEM observation of over-aged specimens showed the formation of Cu precipitates distributed randomly in the matrix for non-deformed specimens [3], whereas the precipitates were distributed in matrix and also along dislocations for pre-deformed specimens. Figure 1 shows the temperature dependence of the Charpy absorption energy for the non-deformed specimens with different aging times. With increasing aging time, the absorption energy curve shifted to the higher temperature side and the DBTT increased. The shift of absorption energy curve was also observed for the pre-deformed specimens by thermal aging. These phenomena are mainly attributable to the increase of yield stress due to Cu precipitation hardening. A similar DBTT shift due to the formation of Cu-rich precipitates was confirmed in neutron irradiated RPV steel with high Cu content [4].

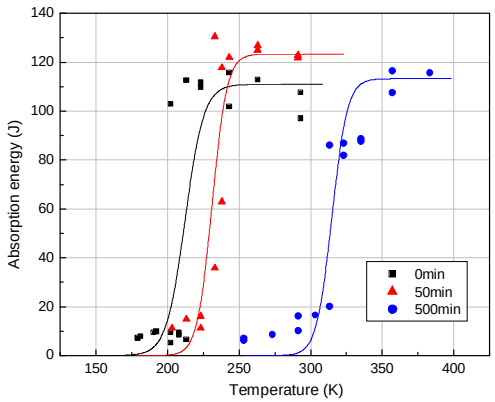

Fig.1 Temperature dependence of Charpy absorption energy in thermally aged Fe–Cu alloys without pre-deformation (CR0%).

Figure 2 shows the *B–H* hysteresis curves of the non-deformed and pre-deformed specimens before and after thermal aging. Magnifications of the *B–H* curves around the H_c are also shown in the insets of Fig. 2. Before thermal aging, the *B–H* curve of the pre-deformed specimen was considerably inclined and the hysteresis loss was much larger than that of un-deformed specimens because of the high dislocation density. After thermal aging, the H_c slightly increased for non-deformed specimens, whereas it was significantly decreased for pre-deformed specimens.

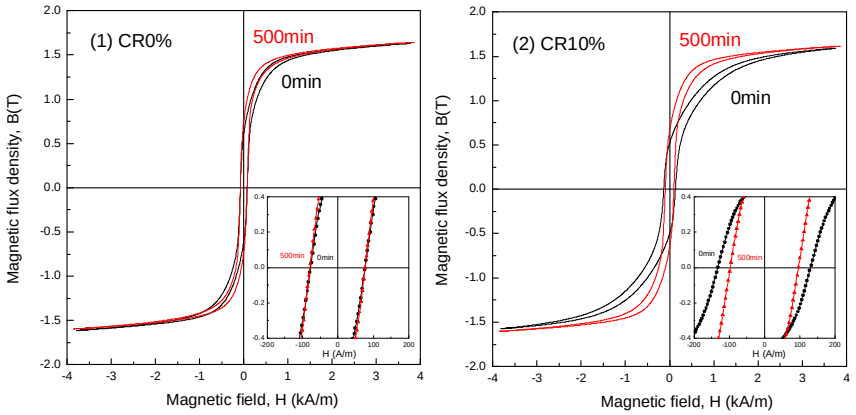

Fig.2 Hysteresis curves of Fe–Cu alloys before and after thermal aging. (1) CR0%, and (2) CR10%.

The relations between DBTT and H_c are summarized in Fig. 3. Both DBTT and Hc increased and a positive correlation was observed for non-deformed specimens, but a negative one was found for pre-deformed specimens. The mechanism of these correlations can be explained as follows. Both dislocation and Bloch wall movement are hindered by Cu precipitates, hence a positive correlation occurs for thermal aging of non-deformed specimens. On the other hand, although the dislocation movement is hindered by precipitates, Bloch wall movement is recovered due to a decrease of the strain field around initial dislocations due to the compensation of internal stress by the strain field of coherent Cu precipitates. This effect must become significant when the initial dislocation density is high as in the case of RPV steels. Actually, similar negative correlations were observed in neutron-irradiated RPV steels [4]. Two types of correlation could be demonstrated by the experiment using thermally aged Fe–Cu specimens, and the underlying mechanism was proposed from the viewpoint of the stress condition around dislocations.

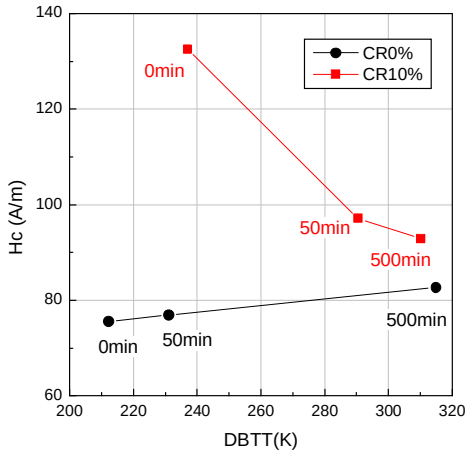

Fig.3 Correlation between Hc and DBTT of thermally aged Fe–Cu alloys.

4. Conclusion

We have investigated the correlation between magnetic properties and DBTT of thermally aged Fe–Cu alloys with and without pre-deformation. With increasing aging time, DBTTs of both specimens increased due to Cu precipitation. The coercive field of as-quenched specimens increased, whereas that of pre-deformed specimens decreased. This phenomenon suggests the importance of the role of initial dislocation density for understanding the magnetic characteristics of irradiated RPV steels.

Acknowledgements:

This research was partly supported under the contract with the Japan Nuclear Energy Safety Organization (JNES).

References

[1] Y. Kamada, T. Nakano, S. Takahashi, K. Ara, H. Kikuchi, J. Echigoya and K. Yaegashi: Proceedings of the 16wcndt (2004).

[2] S. Takahashi, S. Kobayashi, H. Kikuchi and Y. Kamada: J. Appl. Phys., 100 (2006) 113908.

[3] Y. Kamada, D. G. Park, S. Takahashi, H. Kikuchi, S. Kobayashi, K. Ara, J. H. Hong and I. G. Park: IEEE Transactions on Magnetics, 43 (2007) 2701.

[4] S. Takahashi, H. Kikuchi, K. Ara, N. Ebine, Y. Kamada, S. Kobayashi and M. Suzuki: J. Appl. Phys., 100 (2006) 023902.