MAGNETIC EVALUATION OF THE EMBRITLLEMENT ON COLD-ROLLED STEELS

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Abstract: The objective of this study is to demonstrate the correlation between magnetic properties and the degree of embrittlement on cold-rolled steels, and to clarify its underlying mechanism. A Charpy impact test and magnetic hysteresis measurement were performed on Fe-0.15wt.%C steels with different cold-rolling ratios from 0% to 40%. As the cold-rolling ratio was increased, the ductile-brittle transition temperature and coercive field increased simultaneously. This correlation originated from an increase in the dislocation density induced by rolling deformation. This study demonstrates the possibility of applying magnetic methods to pressure vessel surveillance at nuclear power plants.

Introduction: Recently ageing degradation of structural components used in such areas as power plants, pipelines, bridges etc. is becoming a greater concern. The ageing degradation of pressure vessel steels in nuclear power plants is one of the urgent problems to be solved. A Charpy impact test, a destructive evaluation technique, is now used for inspecting the irradiation embrittlement of pressure vessel steels. Since Charpy test pieces are installed inside the reactor before the initial operation, quantities of test pieces are restricted. Now the lifetime of ageing power plants is being extended due to economical and political reasons, which may lead to a shortage of test pieces. Therefore it is necessary to find alternative inspection techniques. Magnetic hysteresis measurement offers a promising way for nondestructive evaluation of degraded ferromagnetic materials because the magnetism is very sensitive to the formation of lattice defects during the degradation process [1]. In order to confirm this idea, we have prepared cold-rolled steels simulating for the embrittlement, and investigated the correlation between ductile-brittle transition temperature (DBTT) and magnetic properties.

Experiments: Fe-0.15wt.%C plates were austenitized at 1173K for 1h and then cold-rolled with different cold-rolling ratios of 0%, 5%, 10%, 20%, and 40%. Three types of specimen were cut from those plates; disk specimens, Charpy V-notch specimens and frame-shaped specimens. Using the disk specimens, transmission electron microscopy observation (Philips, tecnai30, 300keV) was performed for evaluating dislocation structure. Charpy impact test was preformed from 200K to 300K. Magnetic hysteresis was measured at room temperature by using the frame-shaped specimens with wound exciting and detecting coils. Vickers hardness was also measured.

Results: The dislocation density of non-deformed specimens was relatively low and it was estimated as 5×10^{-8} cm^{-2} from TEM observation. As the cold-rolling ratio increased, the black contrast of TEM image became stronger, which indicates a large amount of dislocations were newly produced. Fig.1 shows temperature dependence of Charpy absorption energy for the specimens with different rolling ratios. With increasing the rolling ratio, the energy curve shifted to a higher temperature and upper shelf energy decreased. Similar phenomena are also observed for irradiation embrittlement [2]. These are attributable to the increase of dislocation density by rolling deformation. DBTT of each specimen are summarized in Fig.2 together with the experimental results of hardness. A good correlation between DBTT and hardness was found. With increasing the rolling ratio, DBTT and hardness increased simultaneously. Because the hardness of many metals is known to be proportional to the yield stress [3], it shows that the origin of the increase of DBTT is related to the increase of yield stress.

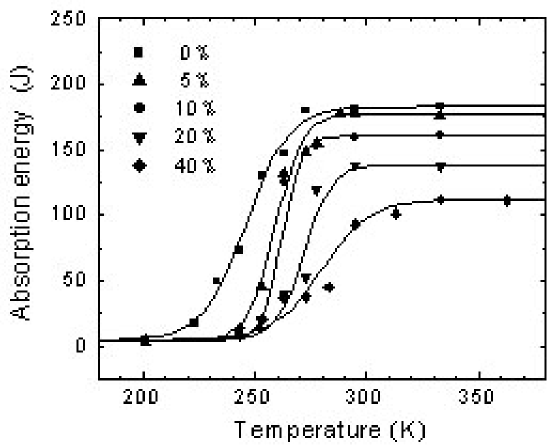

Fig.1. Temperature dependence of Charpy absorption energy.

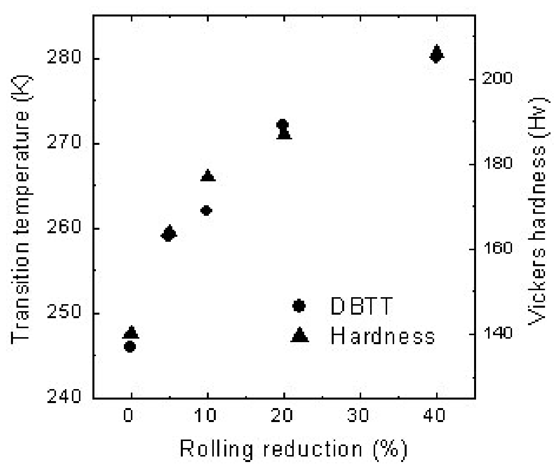

Fig.2. DBTT and hardness as functions of the cold-rolling ratio.

Fig.3 shows the BH curves of the non-deformed and cold-rolled specimens. Before deformation, the specimen is easily magnetized above the coercive field, Hc. With increasing cold-rolling ratio, the specimen becomes less magnetized, and the BH curve becomes inclined. Experimental data of DBTT and coercive field are summarized in Fig.4. With increasing the rolling ratio, both DBTT and Hc increased. Thus we confirmed that there are some correlations between embrittlement and magnetic properties.

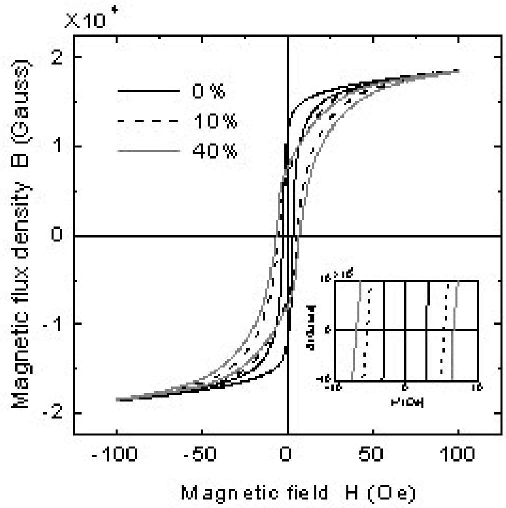

Fig.3. Hysteresis curves of specimens with different cold-rolling ratio.

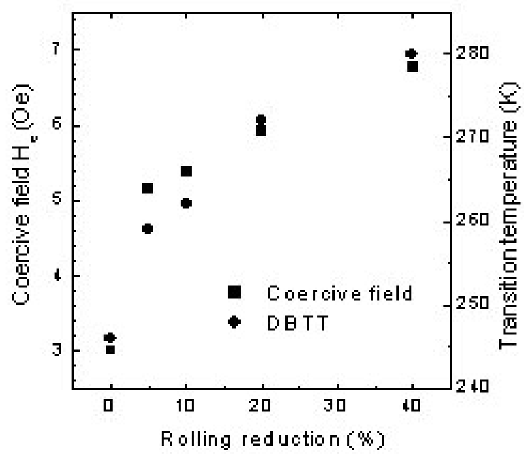

Fig.4. Coercive field and DBTT as functions of the cold-rolling ratio.

Discussion: As the cold-rolling ratio increased, dislocation density, DBTT and Hc increased simultaneously. In order to clarify the physical mechanism of these correlations, the effects of rolling deformation on DBTT will be discussed as a first step.

An increase of dislocation density due to the plastic deformation leads to the increase of yield stress, σ_y, because the formation of dislocation becomes the obstacle of dislocation movement. The relation between yield stress and dislocation density can be expressed as the following [4]:

$$\sigma_y = \sigma_0 + \alpha G b \sqrt{\rho} \qquad (1)$$

Here, σ_0, G, and α denote friction stress, Burgers vector, and a constant value of 0.3 to 0.6 respectively. Fig. 5 shows a schematic representation of Charpy absorption curves and Davidenkov diagram. According to the diagram, DBTT is defined as the temperature at which yield stress and fracture stress, σ_f intersects each other. Although the yield stress increases largely by plastic deformation, fracture stress changes a little. Therefore, only the yield stress curve shifts to upper side as shown in the diagram, and then T_1 of the initial DBTT increases to

T_2. Based on this mechanism of embrittlement, the increment of DBTT, $\Delta DBTT$ is approximately proportional to that of yield stress, $\Delta\sigma_y$.

$$\Delta DBTT \propto \Delta\sigma_y \qquad (2)$$

Combined with the relation of Eq. (1) and Eq. (2), we can conclude that $\Delta DBTT$ is proportional to the increment of the square root of ρ.

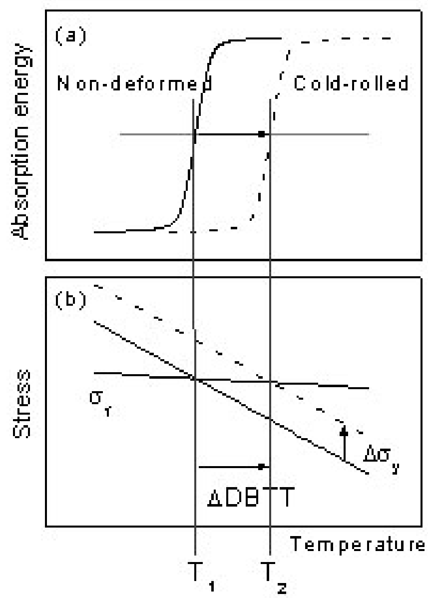

Fig.5. Schematic representation of Charpy absorption curves and Davidenkov diagram.

Next, the relation between magnetic properties and dislocation density will be discussed. Since the internal stress produced by dislocation becomes the obstacle of magnetic domain wall movement, the increase of dislocation density also raises the value of coercive field. It was reported that the coercive field can be expressed as the following [5-6]:

$$Hc = \frac{1}{2M_s F\cos\varphi}\left\langle\left|\Sigma_{\max}\right|\right\rangle_{av} \propto \sqrt{\rho} \qquad (3)$$

Here, M_s, F, φ, and Σ_{max} denotes saturation magnetization, area of domain wall, the angle between magnetization and magnetic field, and the average of total force produced by the internal stress field of dislocation. Σ_{max} is proportional to the square of ρ, which means the coercive field is proportional to the square root of ρ. Combining Eq. (3) with the previous relations of Eq. (1) and (2), the proportional relation between DBTT and coercive field can be obtained. The physical mechanism of the correlation between DBTT and magnetic parameter was clarified and the correlation originated from the increase of dislocation density.

Although the defect structure may be slightly different in the case of the irradiation embrittlement, we confirmed a potential power of magnetic method and found a possibility of applying to the pressure vessel surveillance at nuclear power plants.

Conclusions: We have investigated the correlation between DBTT and magnetic properties of cold-rolled steels. A good correlation between DBTT and Hc could be explained by the increase of dislocation density due to the cold deformation. We could demonstrate the usefulness of magnetic method as a nondestructive evaluation technique for the embrittlement of steels.

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References: [1] S. Takahashi, J. Echigoya and Z. Motoki: J. Appl. Phys., 87 (2000) 805.
[2] M. M. Ghoneim and F. H. Hammad: Int. J. Pres. Ves. & Piping, 74 (1997) 189.
[3] D. Tabor: Brit. J. Appl. Phys., 7 (1956) 159.
[4] G. E. Dieter: Mechanical Metallurgy, p.191 (McGraw-Hill, Boston, 1986).
[5] H. Trauble: Magnetism and Metallurgy, edited by A. E. Berkowitz and R. Kneller, Ch.8 (Academic Press, New York, 1969).
[6] H. Mugrabi, R. Kutterer, K. Lubitz, and H. Kronmuller : Phys. Stat. Sol., (a)38 (1976) 261.