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Magnetic non-destructive evaluation of hardening of cold rolled reactor pressure vessel steel

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ABSTRACT

Non-destructive test (NDT) of reactor pressure vessel (RPV) steel is urgently required due to the life extension program of nuclear power plant. Here magnetic NDT of cold rolled RPV steel is studied. The strength, hardness and coercivity increase with the increasing deformation, and a good linear correlation between the increment of coercivity, hardness and yield strength is found, which may be helpful to develop magnetic NDT of degradation of RPV steel. It is also found that besides dislocation density, the distribution of dislocations may affect coercivity as well.

1. Introduction

Neutron irradiation can bring in damages such as nano precipitates, element segregation and crystalline defects etc., and these irradiation-induced damages will result in degradation of reactor pressure vessel (RPV) [1]. When it comes to the Reactor Life Extension Program, since the number of supervision samples in nuclear power plants is limited, people have explored on non-destructive tests (NDT) to monitor degradation of RPV steel, including coincidence Doppler broadening, small-angle X-ray scattering, Barkhausen emissions, and magnetic test etc. Among them, magnetic NDT has been studied extensively in Fe-Cu alloys and in RPV steels. The magnetic NDT is based on that irradiation damages, such as precipitates and dislocations, could hinder the movement of dislocations as well as the magnetic domain walls, therefore, they will affect both mechanical properties and magnetic properties. If good correlations between magnetic properties and mechanical properties are found, then magnetic NDT could be used to evaluate the degradation of RPV steel. Since neutron irradiation is radioactive and difficulty to obtain, simulation techniques, such as ion irradiation [2], thermal aging [3] and cold working [4], are normally used to simulate irradiation damages. Among them, cold working can be used to bring in extra dislocations to materials on a macro level, on which plenty of characterizations could be carried out.

Koh Yaegashi finds out that after loading up to 540 MPa, the coefficient c of SFVQ-1A steel, which is related to magnetic susceptibility, is proportional to dislocation density [5]and it is sensitive to degradation of mechanical properties during the whole deformation stage [6]. S.Takahashi has systematically studied the relationship between mechanical and magnetic properties in cold rolled S15C steel, including minor-loop coefficients, ductile-brittle transition temperature (DBTT), Vickers hardness (HV), and they find out that there exists a simple relation between minor-loop coefficients and mechanical properties in cold rolled S15C steel, which means that minor magnetic properties is sensitive to lattice defects and may be used in NDT of RPV steel [4,7].

In this paper, cold rolling is used to introduce crystalline defects into RPV steel, then magnetic properties, Vickers hardness and tensile properties are conducted. The variations of remanence, hysteresis loss and coercivity are discussed in detail. Furthermore, the correlation between mechanical properties and magnetic properties is investigated.

2. Materials and methods

Chinese commercial SA508-3 RPV steels supplied by nuclear

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power plant were studied. The initial state of RPV steel was quenched at 1163 K and then tempered at 923 K. The chemical compositions in wt% was shown in Table 1. The RPV steel was cold rolled from 0.75% up to 40.3% reduction in thickness. Then microstructures were observed by JEM-2010 transmission electron microscope (TEM) at 200 kV accelerating voltage. Tensile tests were conducted at room temperature. The accuracy of load force and deformation was 0.5% and 1% respectively, and the displacement rate was 1.6 mm/min. The specimens for tensile test were plate-shaped with 30 mm gauge length and 3 mm thickness. Vickers hardness (HV) tests were measured 8 times for each sample by 5 kgf load force. Magnetic tests were conducted by NIM-2000S soft magnetic instrument up to 18 kA/m magnetic field by ring samples to avoid demagnetization, with 6–8 repeats. The diameter of the ring was 32 mm for inside and 40 mm for outside, and the thickness was about 3 mm. To ensure the accuracy of the test, each sample was stacked by two rings. The turns of exciting coils were about 400, and the turns of induction coils were about 30. The accuracy of magnetic induction and magnetic field were 1% and 2% respectively. Direct current (DC) magnetic properties were studied, including coercivity Hc, remanence Br, saturation magnetic induction Bs and hysteresis loss per cycle WF (WF $= \oint BdH$).

3. Results and discussion

Fig. 1 shows the microstructures of RPV steel of initial state and cold-rolled to different reductions under TEM observation. At initial state, the RPV steel exhibits clear grain boundaries and low dislocation density within grains, as shown in Fig. 1(a). The cold rolled samples could be divided into two groups, the lightly deformed group (from 0% to 4.13% deformation) and the heavily deformed one (from 5.8% to 40.3% deformation). Microstructures of the lightly deformed group are given from Fig. 1(b)–(d). Under low deformation, the grain boundaries act as regions to coordinate the deformation. As the deformation increases, more and more dislocations are introduced around grain boundaries, resulting that the grain boundaries become fuzzier. In the heavily deformed group, the RPV steel shows typical dislocation cell structures, as can be seen from Fig. 1(e)–(j). As the rolling reduction increases, the grains are split into cells within an original grain. More specifically, the cell-like configuration of dislocations consists of cells nearly free from dislocations and cell walls of high dislocations density, as shown in Fig. 1(e).

The results of tensile tests and hardness tests are shown in Fig. 2. Unfortunately, the tensile properties at 0.75% deformation are unavailable since the chunk slipped during the experiment. But generally, the strength and hardness increase consistently as the deformation increases. Strength and hardness reflect resistance to deformation of materials, and are related to the obstacles within materials during deformation. In this experiment, the extra dislocations introduced by cold rolling act as main obstacles to deformation, and the dislocations will hinder other dislocations' movement and introduce extra dislocations into, raising the resistance to deformation, no matter the dislocations are nearby grain boundaries or within grains. So generally, as the dislocation density increases, strength and hardness increase monotonously with deformation.

Fig. 3 shows the magnetic properties of cold rolled RPV steel, including magnetic hysteresis loops, saturation magnetic induction Bs, remanence Br, coercivity Hc and hysteresis loss WF.

As an intrinsic magnetic property, which is independent of the crystalline defects, saturation magnetic induction Bs remains unchanged after cold working. While the remanence Br drops abruptly after lightest deformation, from 1.35T of the initial state to 1.03T, by about 23.7%, and then undergoes a weak decrease at higher deformation. (To make sure the obvious variation of Br in RPV steel resulting from the cold rolling, the magnetic measurement has been repeated for several times using different samples of initial state.) The insert figure in the right corner of Fig. 3(a) shows this trend as well. The magnetic hysteresis loop of initial state shows quite good squareness, while after cold rolling, distortion appears in the upper part, as shown in the insert curves of Fig. 3(a), indicating that the RPV steel after cold deformation becomes more difficult to be magnetized to saturation, and much easier to be demagnetized. Similar remanence decrements of Bs are also reported in welded A533-B and A508 CI.3 steels after neutron irradiation, both in the base zones and weld zone [8,9].

The remanence is an extrinsic magnetic property and it is sensitive to crystal defects. In particular, it relates to the reverse domain nucleation and the domain movement during reversal magnetization. After cold rolling, extra dislocations are introduced into RPV steel, which is normally around the grain boundaries and forms the dislocation cells within grains at higher deformation, as shown in Fig. 1. On one hand, these extra dislocations act as hindrance to domain movement, hindering the magnetization reversal process, which may increase the remanence. On the other hand, these extra dislocations act as reverse domain nucleation sites and ease the reversal magnetization, then decrease the remanence. It seems that in this experiment, the remanence is mainly dominated by the reverse domain nucleation rather than domain movement.

Besides, according to present studies, it seems that the remanence is very sensitive to crystalline defects at tiny deformation, even slight crystalline defects caused by cold working may lead to the decrease of remanence. This is because that even light deformation can activate dislocation sources such as Frank-Read sources, lead to the dislocation multiplication, bring in the nucleation sites for magnetic domain and make ease the reverse magnetization. At higher deformation, the influence caused by crystalline defects tends to saturation.

WF is the integration of magnetic induction and magnetic field, and stands for the hysteresis loss during magnetization. In the study of minor magnetic NDT of RPV steel, WF of minor magnetic loop is always used as a parameter to evaluate irradiation hardening. It is found that WF of minor magnetic loop increases as the matrix damages increase in S15C steel [4] and in Fe metal [10]. In this study, WF of major magnetic loops is studied. As shown in Fig. 3(c), WF generally decreases as the deformation increases, since the demagnetization is much easier after cold rolling. It seems that in major magnetic tests, WF is not always consistent with hardening of materials and may not reflect the hardening of materials directly.

As shown in Fig. 3(c), the coercivity increases as the deformation increases. After cold rolling, extra dislocations introduce extra internal stress, causing the increase of coercivity. The increase of coercivity caused by matrix damages in RPV is not rare, and many researches find that deformation [4,6] and neutron irradiation [9]

Table 1
The chemical composition of RPV steel in wt%.

C	Mn	Ni	Mo	P	S	Cr	Si	Cu	Al	Co	V	Fe
0.18	1.39	0.71	0.47	0.005	0.002	0.12	0.22	0.03	0.01	<0.02	<0.01	Bal