ted samples. The results show that nano-hardness values of the irradiated samples are all higher than that of the un-irradiated sample. Moreover, the nano-hardness value of T91 steel increases with increasing irradiation dose both at RT and 450 ℃, as shown in Fig. 1(a) and (b). Fig. 2(a) shows that the nano-hardness values of irradiated steel to 2.7×10^{15} ions/cm^2 at different temperatures are almost the same within penetrated depth of ~600 nm. When the depth deeper than 600 nm, the nano-hardness value of the sample irradiated at 450 ℃ is higher than that at RT. Fig. 2(b) presents that the nano-hardness values of the samples irradiated to 1.4×10^{16} ions/cm^2 increase with increasing irradiation temperature.

When the irradiation fluence to 2.7×10^{15} ions/cm^2, the displacement damage induced by Fe irradiation is below 2 dpa according to estimated displacement levels by SRIM2008 at the depth of ~ 600 nm, meanwhile, the displacement damage level is higher at deeper region in sample. Therefore, it is suggested that irradiation temperature has little effect on the nano-hardness of the steel when the displacement damage level is below 2 dpa. With increasing irradiation temperature, the nano-hardness value of steel increases at the condition of higher displacement damage level. The nano-hardness is mainly related to the microstructure of the materials induced by irradiation, that is, the formation of point defects and defect clusters at different temperatures and dose.

In summary, irradiation hardening of T91 steel may be caused by the increment of irradiation fluence and temperature. Further investigations on the microstructural changes of T91 steel are undertaken.

3 - 20 Nano-hardness of T91 and SIMP Steels under Helium Ion Implantation at Different Temperatures

Wang Ji, Wang Zhiguang, Yao Cunfeng, Wei kongfang, Cui Minghuan, Sheng Yanbin
Shen Tielong, Li Bingsheng, Zhu Yabin, Pang Lilong, Li Yuanfei, Zhu Huiping
Chang Hailong, Sun Jianrong, Zhang Hongpeng, Wang Dong and Song Peng

The appearance of embrittlement is often accompanied with hardening. Irradiation induced defects (vacancies, interstitials, interstitial/dislocation loops, bubbles and so on) act as obstacles to pin the dislocations from moving, which results in the increase of hardening[1]. In the nuclear reactor, production rate of helium is high by (n, α) reaction and the transmutation production helium is detrimental to mechanical properties of structural materials at different ambient temperatures[2]. The low solubility of helium atoms in structural materials makes it easy to aggregate in sinks, resulting in bubbles, which contribute to the material hardness.

To investigate the temperature effects on irradiation hardening, we performed a series of experiments at 320 keV multi-discipline research platform for highly charged ions. The samples used in the experiments were T91 and SIMP steels that were implanted with 500 keV helium ions to 1.0×10^{17} He/cm^2 at room temperature (RT), 300, 450 and 550 (C, respectively. Then these samples were characterized by nano-indentation measurements. Typical results are shown in Figs. 1 and 2.

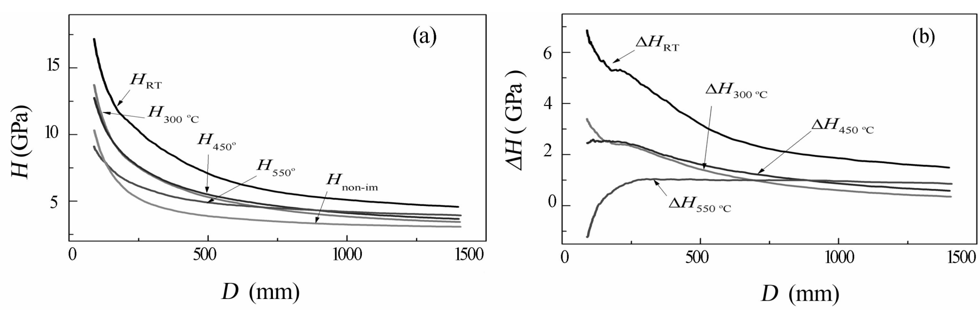

Fig. 1 Hardness H(a) and hardness increment ΔH(b) versus ion penetration depth D of T91 steel bombarded with 500 keV helium ions to 1.0×10^{17} He/cm^2 at room temperature (RT), 300, 450 and 550 ℃.

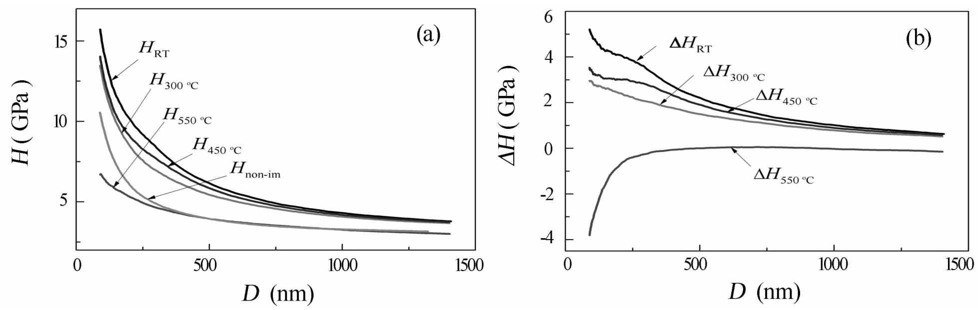

Fig. 2 Hardness H(a) and hardness increment ΔH(b) versus ion penetration depth D of SIMP-7 steel bombarded with 500keV helium ions to 1.0×10^{17} He/cm^2 at room temperature (RT), 300, 450 and 550 ℃.

Fig. 1 shows the hardness H(a) and hardness increment ΔH(b) of T91 steel versus the ion penetration depth D. The subscript index non-im, RT, 300, 450 and 550 ℃ denote the non-implanted sample, the samples implanted at RT, 300, 450 and 550 ℃, respectively. It is clear that the hardness decreases gradually with increasing the ion penetration depth and finally reaches to constants at depth above 1000 nm. In order to further investigate the change of hardness of T91 sample after He-ion implantation, we defined the hardness increment as $\Delta H = H - H_{non\text{-}im}$ that is shown in Fig. 1(b). Compared with the non-implanted T91 sample, ΔH decreases with the implantation temperature, indicating the recovery of irradiation damage at high temperature.

Both of SIMP and T91 steels do not show the increment of hardness with the decrease of temperature monotonously. The sample implanted at 550 ℃ shows the lowest hardness value among the samples, whereas the sample implanted at 450 ℃ shows the largest hardness value. The fact that most ferritic/martensitic steels under helium irradiation have the highest density of helium bubbles at 450 ℃[3] may explain that helium bubbles contribute more than other factors to the hardness of the steels.

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3 - 21 Positron Annihilation Study of Vacancy-type Defects in a F/M Steel under Helium Ion Implantation

Wang Ji, Wang Zhiguang, Yao Cunfeng, Wei Kongfang, Cui Minghuan, Sheng Yanbin
Shen Tielong, Li Bingsheng, Zhu Yabin, Pang Lilong, Li Yuanfei, Zhu Huiping
Chang Hailong, Sun Jianrong, Zhang Hongpeng, Wang Dong and Song Peng

Positron annihilation technique (PAT) is sensitive to atomic-scale vacancy-type defects in solid. Thus it has become an indispensable implement in the study of defects in materials. In this paper, PAT was used to study the vacancy-type defects in a ferritic/martensitic (F/M) steel irradiated by 500 keV helium ions to a dose of 1.0×10^{17} cm^{-2} at room temperature (RT) and 450 ℃.

Fig. 1 shows the Sparameter for non-implanted sample and irradiated samples as a function of positron incident energy. The S parameter shows a remarkable difference between the samples irradiated at RT and 450 ℃. For the sample irradiated at RT, the value of S is larger than that of the non-implanted sample, meaning that extra vacancy defects have been induced by irradiation. For the sample irradiated at 450 ℃, the parameter S is found to be lower than that of irradiated at RT. For the sample irradiated at 450℃, the S parameter is smaller than that of non-implanted sample within 204 nm (corresponding to positron energy of 10 keV). The annihilation of vacancy-type defects by interstitials promoted by temperature play a minor role compared to the increase of defect density. But closer to radiation peak damage, because of the high