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Effects of High Energy Protons on the Mechanical Properties of Fe-2.25Cr-1Mo and Fe-12Cr-1Mo Steels

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Abstract

The radiation damage effects produced by 800 MeV proton irradiation on the tensile properties of the two iron base alloys, Fe-2.25Cr-1Mo and Fe-12Cr-1Mo (HT-9) were determined. It was observed that work hardening rate and uniform strain decreased upon irradiation. The values of Young's modulus were much lower for the irradiated samples than the unirradiated samples. It is thought that this is not due to proton irradiation but mainly due to the difficulties encountered in the tensile test measurements. Proton irradiation caused an increase in the yield strength and ultimate tensile strength and a slight decrease in ductility. Although the rate of work hardening decreased upon irradiation, both iron base alloys showed some degree of work hardening even under high proton fluence. These results indicate that, both alloys can be used as window materials in proton accelerators and as the first wall and structure-blanket materials in nuclear reactors.

Key Words: Proton irradiation, tensile properties, Cr-Mo steels.

Yüksek Enerjili Proton İrradyasyonunun Fe-2.25Cr-1Mo and Fe-12Cr-1Mo Çeliklerinin Mekanik Özelliklerine Etkisi

Özet

Bu çalışmada 800 MeV'lik proton irradyasyonunun Fe-2.25Cr-1Mo ve Fe-12Cr-1Mo çeliklerinin gerilim özellikleri üzerindeki etkileri incelenmiştir. Alaşımların deformasyon sertleşmesinin ve yüzde uzamasının irradyasyon sonucu düştüğü gözlenmiştir. İrradyasyona tabi tutulan örneklerin Young's modülüsleri tabi tutulmayanlara göre daha düşük bulunmuştur. Bunun proton irradyasyonundan ziyade daha çok gerilim testlerinde karşılaşılan güçlüklerden kaynaklandığı zannedilmektedir. Proton irradyasyonu alaşımların akma ve maksimum akma değerlerinde bir artmaya ve sünekliğinde hafif bir düşmeye neden olmuştur. Bu iki demir alaşımının yüksek proton irradyasyonu altında dahi deformasyon sertleşmesi gösterdikleri gözlenmiştir. Elde edilen sonuçlar bu iki alaşımın proton hızlandırıcılarda pencere malzemesi ve nükleer reaktörlerde yapı ve duvar malzemesi olarak kullanılabileceğini göstermektedir.

Anahtar Sözcükler: Proton irradyasyonu, mekanik özellikler, Cr-Mo çelikleri.

Introduction

High energy proton accelerators have been used for radiation damage studies of many materials using the direct proton beam and spallation neutrons produced at the beam stop. Characterization of radiation damage induced by high energy protons has been gaining considerable attention, due to the possibilities of extrapolating this information to high energy neutron damage produced in nuclear fission and especially in fusion environment. It has been shown that, the damage characteristics of high energy proton irradiation are very similar to those of fission and fusion neutrons, however, the mechanisms of the energy transfer to the lattice atoms are quite different. The high energy protons produce spallation reactions in the target atoms. As a result of these spallation reactions materials experience a special type of radiation damage and deposit a large amount of energy, that causes atomic displacements and the production of a high rate of hydrogen, helium and heavier transmutation products in materials (Wechsler and Sommer, 1984).

The Los Alamos Meson Physics Facility (LAMPF) and The Swiss Institute for Nuclear Research (SIN) have proton accelerators that accelerate protons to 800 and 600 MeV, respectively. These accelerators have been extensively used to carry out general radiation damage studies (Singh et al., 1982, Sommer et al., 1983). During the radiation damage experiments, some of their structural materials such as beam line windows, beam line stops and targets are heavily radiation damaged. Therefore, it is necessary to develop specific materials for their own parts that can serve better during the radiation experiments. This work was undertaken to test two iron based materials for the beam line windows. Materials that would be choosen for this service must be compatible with the molten Pb-Bi and retain reasonable strength and ductility under irradiation experiments.

Initial studies and examinations indicated that Fe, Ta, and iron base alloys; Fe-2.25Cr-1Mo and Fe-12Cr-1Mo could be candidates for the application of the beam line windows. The Cr-Mo steels are also considered to be primary candidates for the first wall and structure-blanket materials for fusion and fission reactors (Klueh and Vitek, 1984). Therefore, it was decided to investigate the effects of 800 MeV proton irradiation on the tensile properties of Fe and Ta metals, and two iron base alloys. In the first work (Öztürk et al., 1994), we reported the results of proton irradiation on Fe and Ta metals and we now present the results of 800 MeV proton irradiation on the tensile properties of the two steel alloys.

Experimental

The tensile test samples were prepared from 0.5 mm-thick sheet of Fe-2.25Cr-1Mo and Fe-12Cr-1Mo steels and were heat treated in a high-vacuum furnace. Fe-2.25Cr-1Mo samples were first held at 1213 K for 7 min. and then at 873 K for 30 minutes. Similarly, Fe-12Cr-1Mo samples were first held at 1323 K for 7 min. and then at 973 K for 60 minutes in the furnace. The samples were then sealed inside iron capsules containing Pb-Bi liquid and were proton irradiated to the low fluence of 4.8×10^{23} protons/m^2 and high fluence of 5.4×10^{24} p/m^2 using the proton accelerator at the LAMPF facility. The power deposited by the proton beam in the capsules was sufficient enough to sustain the samples at a temperature of about 673 K.

Post-irradiation examination of samples showed that there was no corrosion on the samples due to the molten Pb-Bi liquid. Following proton irradiation tensile tests were conducted at room temperature at a nominal crosshead speed of 8.5×10^{-3}mm/s, which for the gage length of 9.5 mm resulted in a strain of 9×10^{-4}s^{-1}. A clip-on extensometer was used during the first part of the tensile test. At about 5% strain, it was necessary to remove the extensometer and the tensile test was continued with cross-head displacement to measure the strain. From these tests the load-distance charts were obtained for the all samples.

Result and Discussion

The application of 800 MeV proton irradiation resulted in significant changes on the mechanical properties of the investigated steels. The effect of proton irradiation on the strength, ductility, Young's modulus, and work hardening of the both steels are discussed in the following headings.

Effect of Proton Irradiation on Strength and Ductility

The applied tensile stress required to induce plastic behaviour is known as the elastic limit or the yield stress. This stress is very important in structural design because it marks the limit over which large deformations are produced by small increases in stress. The maximum load that a material can withstand defines another important property called the ultimate tensile strength.

Proton irradiation resulted in an increase in yield stress and ultimate tensile strength and a decrease in ductility of the two iron alloys. As seen from Figures 1 and 2, the decrease in ductility and increase in strength is much larger in Fe-2.25Cr-1Mo than Fe-12Cr-1Mo alloy. These two alloys undergo some work hardening even upon high proton fluence and the ductility are not greatly reduced with compared to the pre-irradiation values. It is commonly believed that radiation-produced defects are responsible for strengthening and loss of ductility of irradiated materials.

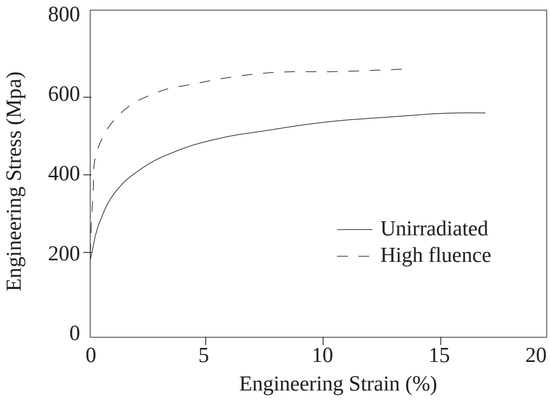

Figure 1. Effect of proton irradiation on the tensile properties of Fe-2.25Cr-1Mo

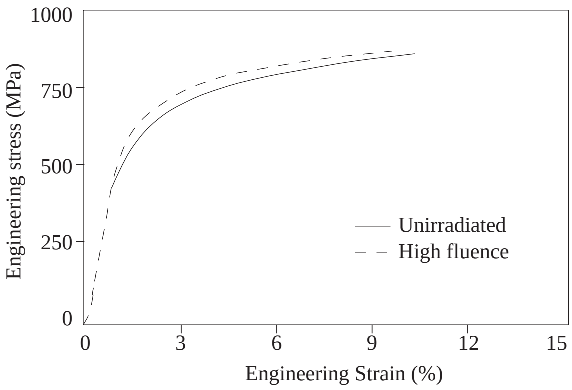

Figure 2. Effect of proton irradiation on the tensile properties of Fe-12Cr-1Mo

Effect of Proton Irradiation on Young's Modulus

When solid materials are subjected to low stresses, they usually respond in an elastic fashion; that is, the strain produced by the stress is reversible, which means that the strain returns to zero when the stress is removed. Also, the strain (ϵ) is proportional to stress (σ) in this region as expressed by Hooke's law. For an uniaxial applied tensile stress, σ, Hooke's law is simply given by

$$\sigma = E\epsilon \tag{1}$$

where, the constant of proportionality, E, is known as the elastic modulus or the Young's modulus (Bloom and Weir, 1972). This relationship is normally valid only in elastic region.

Since the Young's modulus is an important tensile property that determines the application areas of materials, it is desired to know how it is affected by radiation environment where the materials could be used. To evaluate the values of the Young's modulus for the samples of the two alloys the load-distance charts were first converted to the engineering stress-strain diagrams. Young modulus of the samples were assumed to be the maximum slopes of the stress-strain curves in the elastic region (Öztürk et al., 1994). The calculated values of Young's modulus of the unirradiated, low irradiated, and high irradiated samples of Fe-2.25Cr-1Mo and Fe-12Cr-1Mo alloys are tabulated in Tables 1 and 2, respectively. It can be seen from these tables that there is a considerable deviation between the values of Young's modulus, especially between the unirradiated samples of Fe-2.25Cr-1Mo alloy. This indicates that, the tensile tests were very crude. Consequently, the obtained values of Young's modulus could be lower than the actual values for some samples. Especially, this may be the case for the irradiated samples, for which the proper alignment of the samples in the tensile machine was particularly difficult.

In this study, the obtained average values of the Young's modulus of the unirradiated samples of Fe-2.25Cr-1Mo and Fe-12Cr-1Mo alloys are 145 and 51.2 GPa and the literature values are 206 and 186 GPa (Barret et al., 1973). The obtained value for the Fe-12Cr-1Mo alloy is very low compared to the literature value.

Table 1. Young's modulus for Fe-2.25Cr-1Mo samples

Samples	Young's modulus (GPa)
Unirradiated	
C-14	193.4
C-15	199.3
C-16	108.3
C-17	81.43
Low irradiated	
C-2	33.99
C-3	41.92
C-12	31.58
C-13	63.71
High irradiated	
C-6	40.54
C-7	44.47

Table 2. Young's modulus for Fe-12Cr-1Mo samples

Samples	Young's modulus (GPa)
Unirradiated	
HT-11	52.33
HT-12	50.06
Low irradiated	
HT-2	16.06
HT-9	34.40
HT-10	14.68
High irradiated	
HT-4	26.20
HT-5	37.99

Effect of Proton Irradiation on Work Hardening

At stress higher than yield point stress-strain relationship deviates from linearity and Hooke's law is no longer valid. This region is known as, the plastic deformation region and is characterized by the fact that, the deformation occurs permanently in this region. When stress is removed, the materials unloads elastically, but a permanent strain remains in material. The increase in stress required to continue the plastic deformation at a given strain rate in the plastic region is called work hardening or strain hardening. The more a material is plastically deformed, the more difficult it becomes to plastically deform the material further. As plastic deformation continues, the cross-sectional area decreases, but the load carrying capacity of the specimen increases due to work hardening. In the plastic region, the relation between the stress and strain is governed by the Holloman equation;

$$\sigma_t = K\epsilon_t^n \tag{2}$$

where σ_t and ϵ_t are the true stress and true strain, K is the strength constant, and n is the work hardening exponent. Taking natural logarithm of Eq. 2 yields

$$Ln\sigma = \ln K + n\ln\epsilon \tag{3}$$

which is a straight line equation.

For the two iron base alloys, the engineering stress-strain curves were converted to the true stress-strain curves and the data between 0.2% offset yield stress and ultimate tensile strength were fitted to Eq. 3 to obtain the constants K and n. The calculated values of K, n, and true uniform strain are given in

Tables 3 and 4 for the two alloys. To check the goodness of the fit to the actual data distributions the correlation coefficient, R^2 values were calculated. For all the samples tested, the value of R^2 was found to be between 0.95 and 0.99. Since the larger is R^2, the better is the fit, it can be said that the Holloman equation describes quite well the observed true stress-true strain curves in the work hardening region.

Table 3. Work hardening parameters for Fe-2.25Cr-1Mo

Samples	Strength coefficient (GPa)	Work hardening exponent, n	True uniform strain
Unirradiated			
C-14	0.936	0.180	0.136
C-15	0.999	0.195	0.160
C-16	0.809	0.200	0.170
C-17	0.944	0.179	0.160
High irradiated			
C-6	1.100	0.129	0.127
C-7	0.915	0.107	0.116

Table 4. Work hardening parameters for Fe-12Cr-1Mo

Samples	Strength coefficient (GPa)	Work hardening exponent, n	True uniform strain
Unirradiated			
HT-11	1.477	0.173	0.087
HT-12	1.521	0.176	0.095
High irradiated			
HT-4	1.605	0.230	0.126
HT-5	1.653	0.193	0.105

It has been generally observed that radiation causes a reduction in the strain hardening exponent, n and the uniform strain (Brown and Cost, 1982). This is also observed on the Fe-2.25Cr-1Mo alloy, but not on the Fe-12Cr-1Mo alloy, as seen in Tables 3 and 4. On the contrary an increase in n and uniform strain is observable on the irradiated samples of the Fe-12Cr-1Mo alloy. The reason for this increase is not clear. It may be due to the tensile test conditions mentioned before or it may be direct result of proton irradiation.

The value of the work hardening exponent should be close to the value of the true uniform strain if the work hardening equation fits the true stress-strain curves. But the value of n is much larger than the true uniform strain for the Fe-12Cr-1Mo alloy, which may suggest that the increase in n upon irradiation is not due to proton irradiation but mainly due to the tensile test conditions. Unlike pure metals Fe and Ta which exhibited plastic instability (Öztürk et al., 1994), the irradiated Fe-2.25Cr-1Mo and Fe-12Cr-1Mo alloys showed some degree of work hardening following high fluence irradiation as seen from Figures 1 and 2. The decrease in the work hardening exponent and the rate of work hardening upon irradiation is explained by the dislocation channeling, which has been observed in many metals and alloys (Wechsler, 1973).

Conclusions

In general 800 MeV proton irradiations produced an increase in the yield stress and ultimate tensile stress and a decrease in the rate of work hardening, uniform strain, and ductility. It was difficult to draw conclusions on Young's modulus due to some difficulties encountered in the tensile test experiments. However, the obtained values of Young's modulus for the irradiated samples are quite low compared to the value of the unirradiated samples. On the bases of the measured strength and ductility, it seems that either one of these iron base alloys, Fe-2.25Cr-1Mo or

Fe-12Cr-1Mo, could be a suitable alloy for the proton beam window in contact with Pb-Bi as long as window temperature is maintained at a temperature below 673 K. The increase in their strength upon radiation also makes them potential candidates as the first wall and blanket-structure materials for fission and fusion reactors.

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