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Superior Charpy impact properties of ODS ferritic steel irradiated in JOYO

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Abstract

The effect of neutron irradiation on Charpy impact properties of an ODS ferritic steel developed by PNC was studied. The miniaturized Charpy V-notch (MCVN) specimens (1.5 × 1.5 × 20 mm) of two orientations (longitudinal, called 1DS-L, and transverse, 1DS-T) were irradiated to fluence levels of (0.3–3.8) × 10^{26} n/m^2 ($E_n > 0.1$ MeV) between 646 and 845 K in JOYO. MCVN specimens before and after the irradiation were subjected to instrumented Charpy impact tests. The test results and fracture surface observations showed that in the unirradiated state the steel showed no ductile-to-brittle transition behavior until 153 K regardless of orientation and the upper shelf energy of the steel was as high as that of a high-strength ferritic steel without dispersed oxide. Such excellent impact properties were essentially maintained after the irradiation although an appreciable decrease in absorbed energy occurred by higher temperature irradiations at and above 793 K.

1. Introduction

An oxide dispersion strengthened (ODS) ferritic steel developed by PNC (Power Reactor and Nuclear Fuel Development Cooporation) for advanced fast breeder reactor core applications is considered to be very promising for fusion structural applications since they are expected to exhibit excellent swelling resistance and superior high temperature strength. Therefore, recently many studies were performed [1–7]. However, ferritic steels including ODS steels are known to exhibit ductile-to-brittle transition behavior and significant embrittlement by irradition. Therefore, it is needed to improve the resistance to irradiation embrittlement.

It was reported that the matrix in the ODS ferritic steel recently developed by PNC included a high density of Y–Ti–O oxide particles with the size of ultra-fine scale of several nm [3–5]. Such extremely fine oxide particles in matrix may have the beneficial effect of suppressing the irradiation damage significantly and thereby improving the resistance to irradiation embrittlement. The objective of this study is to examine the Charpy impact properties of the ODS ferritic steel before and after neutron irradiation to 3.8 × 10^{26} n/m^2 in JOYO, the fast experimental reactor at PNC. It will be shown that the ODS steel exhibits superior Charpy impact properties before and after neutron irradiation.

2. Experimental

The ODS ferritic steel used in this study was developed by PNC for advanced fast breeder reactor core applications and was designated as 1DS [4]. The chemical composition of the steel is given in Table 1. The steel included a high density of Y–Ti–O complex oxides with an average size of as small as 3 nm which were produced from original Y_2O_3 powders during mechanical alloying

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Table 1
Chemical composition of 1DS developed by PNC (wt%)

C	Si	Mn	P	S	Ni	Cr	W	Ti	Ex.O [a]	N	Y_2O_3	Fe
0.09	0.05	0.03	0.003	0.002	0.15	10.98	2.67	0.40	0.070	0.01	0.66	Bal

[a] Ex.O means excess oxygen which does not form Y_2O_3.

and the following annealing process. Miniaturized Charpy V notch (MCVN) specimens were machined with the dimensions of 1.5 mm × 1.5 mm × 20 mm and the notch geometry of 0.3 mm in notch depth, 0.08 mm in notch root radius and 30° in notch angle [8]. The specimen with the longitudinal direction parallel to the rolling direction is called 1DS-L and that with the transverse one 1DS-T.

Neutron irradiation was performed for MCVN specimens to four levels of 0.3×10^{26} n/m^2 to 3.8×10^{26} n/m^2 (E_n > 0.1 MeV) at temperatures from 646 to 845 K in JOYO. Conditions of irradiation for 1DS-L and 1DS-T are shown in Table 2. For both irradiated and unirradiated MCVN specimens the instrumented Charpy impact test was conducted at temperatures from 153 to 403 K. In the test, specially designed electrohydraulic servo-controlled testing machine was used with a span of 12.5 mm and an impact testing velocity of approximately 5 m/s [9]. Fracture surfaces of impact tested specimens were examined by scanning electron microscopy.

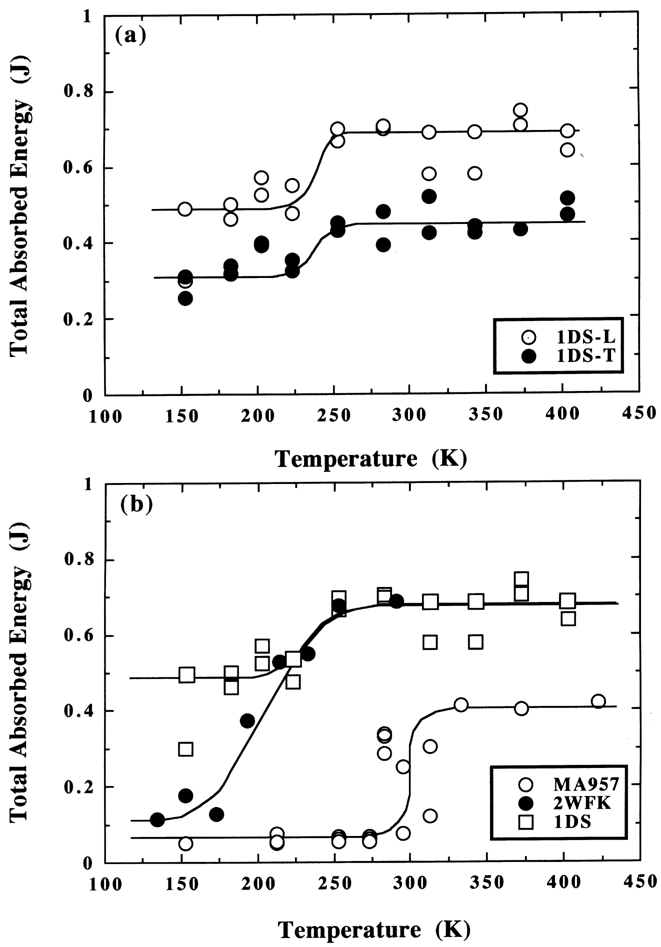

Fig. 1. Test temperature dependence of total absorbed energy for unirradiated MCVN specimens of 1DS-L and 1DS-T (a) and of MA957, 2WFK and 1DS-L (b).

Table 2
Designation and irradiation conditions in JOYO

Designation	Temperature (K)	Fluence (E_n > 0.1 MeV) × 10^{25} n/m^2
1DS-L		
PS-1	646	3
PS-2	753	5
PS-A	793	14
1DS-T		
PS-3	646	3
PS-4	650	5
PS-B	667	14
PS-C	775	38
PS-F	845	38

3. Results and discussion

Fig. 1(a) shows the test temperature dependence of total absorbed energy for unirradiated 1DS-L and 1DS-T. It is obvious that for 1DS-L and 1DS-T there is a transition from the upper to lower shelf regions at around 230 K. However, the value of the lower shelf energy (LSE) is as high as about 65% of the upper shelf energy (USE) for both 1DS-L and 1DS-T. To the authors' knowledge, such a high level of LSE has never been reported for ferritic steels. SEM micrographs of fracture surfaces for 1DS-L and 1DS-T showed the occurrence of fibrous fracture even in the lower shelf region, as shown in Fig. 2. There results indicate that 1DS is essentially ductile even in the low temperature range down to 153 K. In other words, the ductile-to-brittle transition behavior, that is, the ductile-to-brittle transition temperature (DBTT) is absent for 1DS, which is a notable property of this alloy. This was confirmed also by load-displacement curves obtained in the lower shelf region, since the curves did not show sudden drop of load, which is an indication of brittle fracture, as mentioned later (Fig. 4). Another result to be noted is that there is anisotropy in USE and LSE; the values of USE and LSE are considerably higher in 1DS-L than in 1DS-T. This anisotropy in USE and LSE; the values of USE and LSE and LSE are considerably higher in 1DS-L than in 1DS-T. This anisotropy may be attributed to the elongated bamboo-like grain structure of 1DS [3,4].

The total absorbed energy versus test temperature curves for unirradiated 1DS-L were compared with those of MCVN specimens for other ferritic steels and are shown in Fig. 1(b). MA957 is a commercially available Y_2O_3-dispersed ferritic alloy. 2WFK is a high-strength ferritic steel without dispersed oxide (11 Cr–0.5 Mo–2.0W–0.2V) [10]. As seen from the figure, the USE of 1DS-L is almost equal to that of 2WFK and is about twice as high as that of MA957. Furthermore, the LSE

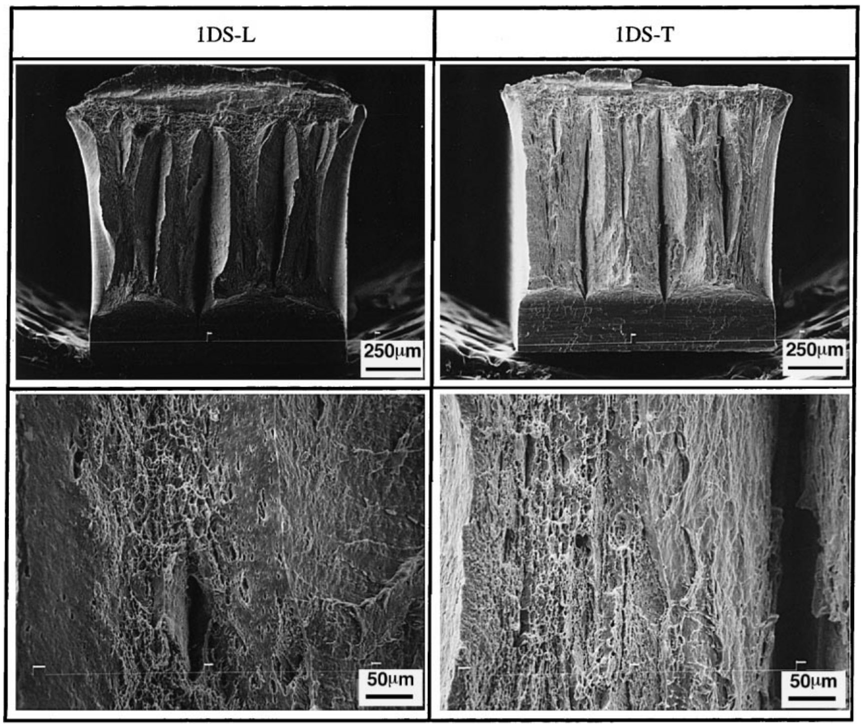

Fig. 2. SEM micrographs of fracture surface for unirradiated 1DS-L and 1DS-T tested at 183 K.

of 1DS-L is considerably higher than the USE of MA957, while the LSE for MA957 and 2WFK is very low. MCVN specimens of MA957 and 2WFK tested in the lower shelf regions showed flat-like brittle fracture surfaces and a sudden, large drop in load-displacement curves. Therefore, we can say that 1DS shows superior Charpy impact properties, especially at low temperatures.

Fig. 3 shows the test temperature dependence of total absorbed energy for 1DS-L and 1DS-T irradiated under different conditions. The irradiation at and below 775 K does not cause appreciable change of total absorbed energy in the test temperature range studied. This means that the above superior properties of 1DS are maintained after irradiation to fairly high levels as far as the irradiation temperature is 775 K and below. At and above 793 K, on the other hand, 1DS exhibits irradiation embrittlement; an appreciable decrease in USE and LSE occurred by the irradiation at 845 K for 1DS-T and by the irradiation at 793 K for 1DS-L. However, such embrittlement is not significant and the LSE is still fairly high. This is confirmed from Fig. 4, which shows the load-displacement curves in the upper and lower shelf regions for 1DS-L before and after irradiation at 793 K which caused appreciable embrittlement. The curve at 173 K appears to show no indication of brittle fracture, as is the case for all curves obtained. Therefore, it is reasonable to say that 1DS has high resistance to irradiation embrittlement.

In order to study the cause of the embrittlement observed in the higher temperature irradiation, the relationship between irradiation embrittlement and irradiation hardening was examined. Fig. 5 shows the effect of irradiation on dynamic yield load measured by Charpy impact tests for 1DS-L. It is seen that the irradiation hardening occurs by 15–30% and the amount of the hardening is almost the same between PS-1, PS-2 and PS-A. However, only PS-A showed appreciable irradiation embrittlement. Similar results were obtained for 1DS-T. These results bring the suggestion that the

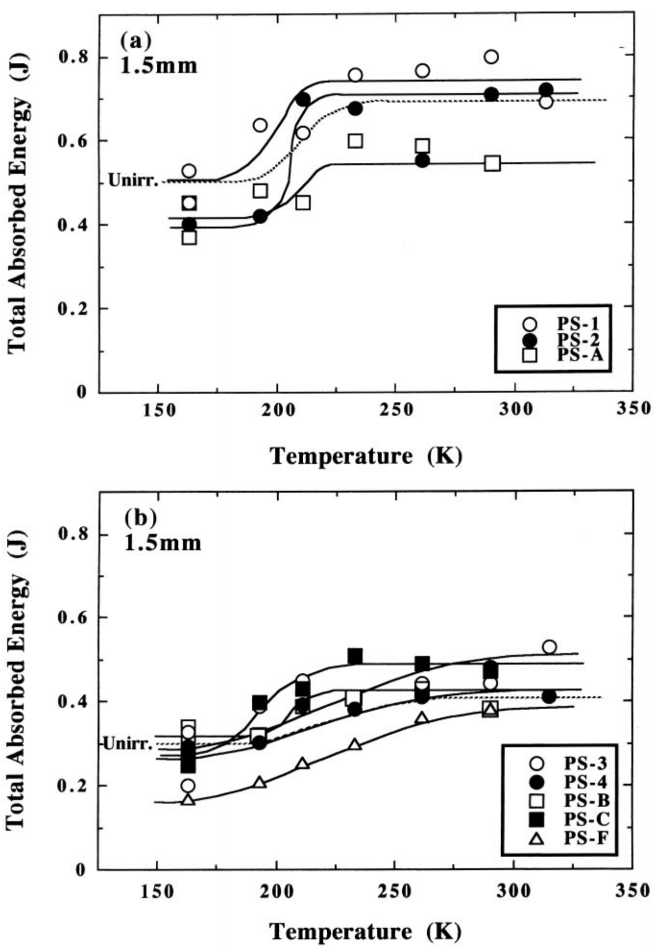

Fig. 3. Test temperature dependence of total absorbed energy for 1DS-L (a) and 1DS-T (b) that were irradiated under different conditions (see Table 2).

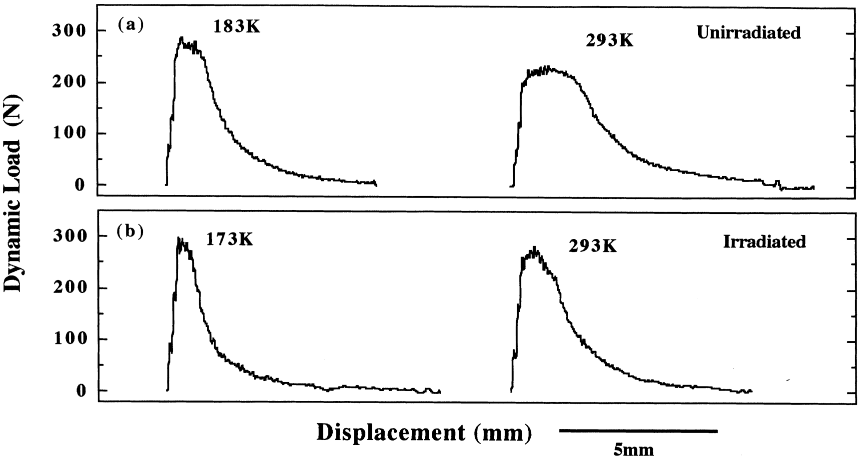

Fig. 4. Load-displacement curves obtained by instrumented Charpy impact tests for 1DS-L unirradiated (a) and irradiated to 1.4×10^{26} n/m^2 at 793 K (b).

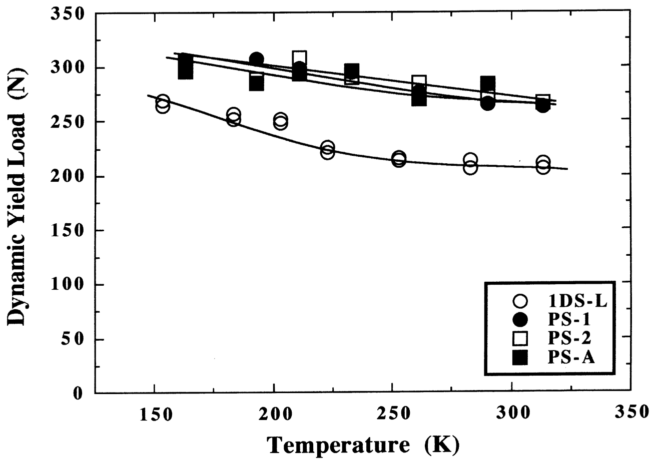

Fig. 5. Test temperature dependence of dynamic yield load for 1DS-L unirradiated (○) and irradiated under different conditions (●,□,■).

observed irradiation embrittlement is not caused by irradiation hardening. Further studies should be needed to clarify the cause of embrittlement.

4. Conclusion

The Charpy impact properties of an ODS ferritic steel developed by PNC and designated as 1DS-L (longitudinal orientation) and 1DS-T (transverse orientation) were studied before and after irradiation to fluence levels of $(0.3–3.8) \times 10^{26}$ n/m^2 ($E_n > 0.1$ MeV) at temperatures from 646 to 845 K in JOYO.

In the unirradiated state, the absorbed energy showed a transition from the upper to lower shelf regions at around 230 K for both 1DS-L and 1DS-T. However, in the lower shelf region the LSE was as high as about 65% of USE and ductile fracture surface was observed. This indicates that the ductile-to-brittle transition behavior and thus DBTT are absent in the temperature range down to 153 K for 1DS.

The irradiations at and below 775 K caused no appreciable change in absorbed energy for 1DS-L and 1DS-T. After the irradiation at and above 793 K, 1DS exhibited an appreciable decrease in USE and LSE, however, such embrittlement was not significant. In the lower shelf region the LSE was still high and 1DS showed ductile fracture. It is reasonable to say that 1DS has high resistance to irradiation embrittlement.

The irradiation hardening obtained by Charpy impact tests was 15–30%. However, the amount of the hardening was almost the same regardless of whether or not the irradiation embrittlement occurred, indicating that the irradiation hardening is not responsible for the observed irradiation embrittlement.

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