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Preliminary analysis of irradiation effects on CLAM after low dose neutron irradiation

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A B S T R A C T

To investigate the irradiation effects on a new version of reduced activation ferritic/martensitic steels (RAFMs) i.e. China Low Activation Martensitic steel (CLAM), neutron irradiation experiments has been being carried out under wide collaboration in China and overseas. In this paper, the mechanical properties of CLAM heats 0603A, 0408B, and 0408D were investigated before and after neutron irradiation to ~0.02 dpa at 250 °C. The test results showed that ultimate strength and yield stress of CLAM HEAT 0603A increased about 10–30 MPa and ductile to brittle transition temperature (DBTT) shift was about 5 °C. For CLAM heats 0408B and 0408D, ultimate strength and yield stress increased about 80–150 MPa.

1. Introduction

Reduced activation ferritic/martensitic steels (RAFMs) are presently considered as the primary candidate structural material for future fusion reactors based upon their low residual radioactivity, good resistance to void swelling, good thermal stress resistance and relatively mature material fabrication technologies etc. [1–4]. The structural materials for future fusion reactors will undergo high displacement damage by intense flux of high energy neutrons. So neutron irradiation experiments on candidate fusion structural material were widely carried out to investigate the irradiation effects. The effects of irradiation on the mechanical properties depend on irradiation temperature; for irradiations above 400 °C, properties are generally unchanged, although the occurrence of radiation-enhanced softening has been reported. Changes in mechanical properties tend to saturate with increasing dose; for some RAFM steels, saturation has been observed around 10 dpa [5].

Research on a new version of RAFMs i.e. China Low Activation Martensitic steel (CLAM) was started five years ago at ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences) under wide collaboration with other institutes and universities in China. Most of its properties tested before irradiations are similar to those of the other RAFMs under wide research in the world [1,6–10]. And CLAM is chosen as the candidate structure material of the FDS series fusion reactors [11–13] and ITER liquid LiPb Test Blanket Module of China [14–16]. To investigate the irradiation effects on CLAM, neutron irradiation experiments are being carried out under wide collaboration in China and overseas.

In this paper, the low dose neutron irradiation experiment on CLAM specimens to 0.02 dpa at 250 °C was introduced. The effects of low dose neutron irradiation on mechanical properties of CLAM were analyzed. Besides, irradiation effects on CLAM and other RAFMs under similar irradiation conditions were introduced and compared.

2. Experimental

The steels used were HEAT 0408B, HEAT 0408D and HEAT 0603A of CLAM. Their chemical compositions are listed in Table 1. HEAT 0408B and HEAT 0603A are the alloy with normal composition design and 0.3% silicon was added in HEAT 0408D to investigate the effect of silicon on the mechanical property.

The specimens of HEAT 0408B and HEAT 0408D were from 20 kg ingot, which was hot-forged and rolled into a 6 mm-thick plate and 12 mm-thick plate. The specimens of HEAT 0603A were from 300 kg ingot, which was hot-forged and rolled into a 12.5 mm-thick plate. The heat treatments included normalization (980 °C/30 min/air cool) and tempering (760 °C/90 min/air cool). The details of metallurgical process and composition for them can be found in Refs. [1,7].

Specimens of CLAM were irradiated in a fission reactor to 0.02 dpa at 250 °C. Tensile tests using 51 mm length specimens with a gage part of $\Phi 4 \times 20$ mm were carried out at room temperature (RT), 150 °C, 200 °C and 300 °C in a static tensile machine at a cross-head speed of 0.1 mm/min before yield point and 5 mm/min after yield point. The lower deformation rate before yield point was to investigate the elastic deformation of specimens. Charpy impact tests using specimens ($55 \times 10 \times 10$ mm) with a $45° \times 2$ mm V-notch were performed in the test temperature range from −120 °C to 60 °C.

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Table 1
Chemical compositions of different heats of CLAM steel (wt%).

	Cr	W	V	Ta	Mn	C	Si
HEAT 0408B	8.91	1.44	0.20	0.15	0.49	0.12	0.11
HEAT 0408D	8.91	1.44	0.20	0.15	0.49	0.12	0.27
HEAT 0603A	8.93	1.44	0.20	0.15	0.45	0.13	0.08

3. Results and discussion

3.1. Tensile properties

Fig. 1 shows the strength and elongation for HEAT 0603A before and after irradiation. The ultimate strength and yield stress increased about 10–30 MPa. Total elongation decreased about 4% at 200 °C and 350 °C but increased about 4% at RT and 100 °C. And the reduction of area decreased 1–4% at different temperatures.

It was reported that the increase of strength of 9Cr2WVTa after 0.015 dpa neutron irradiation at 60–100 °C was 30 MPa and total elongation decreased about 6% [17]. So hardening of CLAM was slight, after low dose neutron irradiation.

Fig. 2 shows the strength and elongation for HEAT 0408B before and after irradiation. The ultimate strength increased about 80–120 MPa and yield stress increased about 100–150 MPa. Total elongation decreased about 6% at RT. The specimens before irradiation are 6 mm-thick plate.

Fig. 3 shows the strength and elongation for HEAT 0408D before and after irradiation. The ultimate strength increased about 100 MPa and yield stress increased about 80–150 MPa. Total elongation decreased about 8%. The specimens before irradiation are 6 mm-thick plate.

For the tensile results of HEAT 0408B and HEAT 0408D, there is no obvious silicon effect on the irradiation hardening. Irradiation induced hardening of HEAT 0408B and HEAT 0408D are much larger than that of HEAT 0603A. To determine the source of these much higher hardening levels, detailed microstructural characterization investigation is underway.

3.2. Impact properties

Fig. 4 shows the charpy impact curves for HEAT 0603A before and after irradiation, fitted with hyperbolic tangent function. The ductile-brittle transition temperature (DBTT), obtained at the temperature corresponding to half the difference between the upper-shelf energy and lower-shelf energy, increased about 5 °C after irradiation.

It was reported that the DBTT shift of JLF-1 after 0.01 dpa neutron irradiation at 297 °C was 50 °C [18]. The embrittlement of

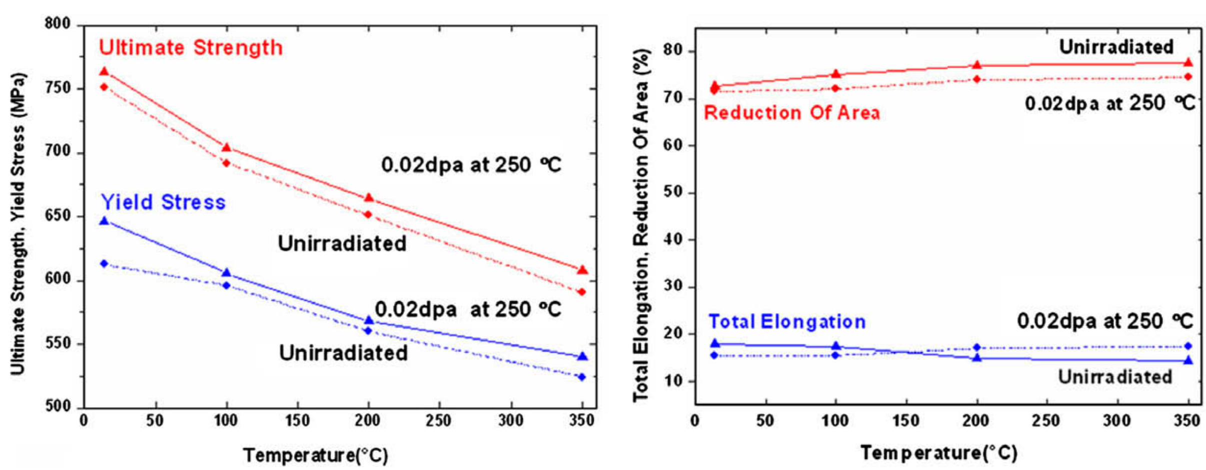

Fig. 1. Tensile properties of CLAM (HEAT 0603A).

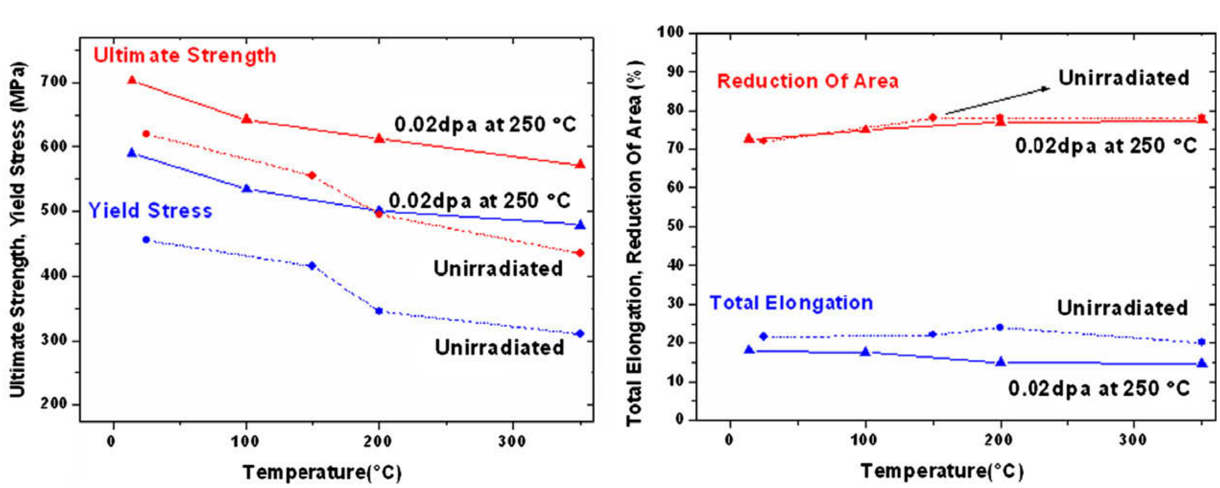

Fig. 2. Tensile properties of CLAM (HEAT 0408B).

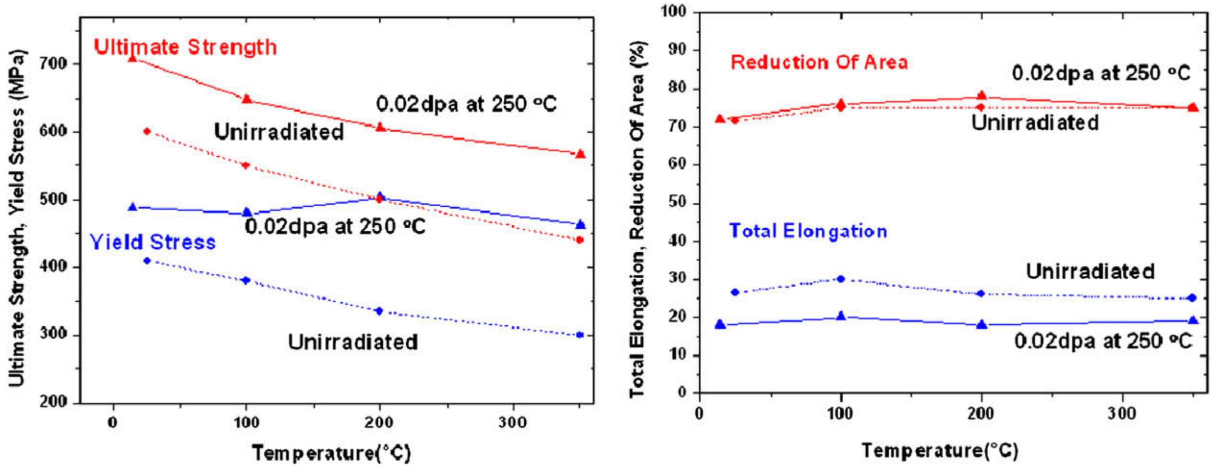

Fig. 3. Tensile properties of CLAM (HEAT 0408D).

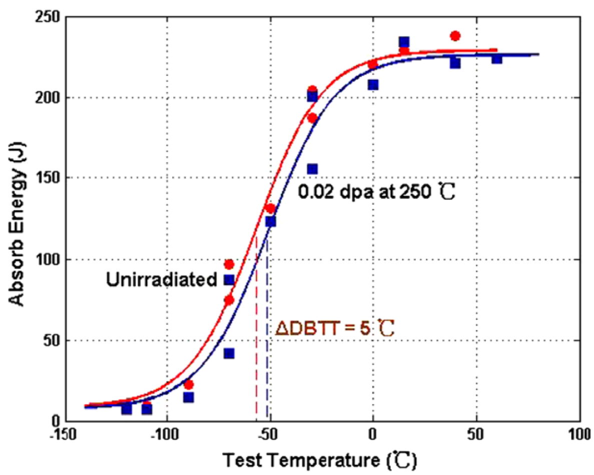

Fig. 4. Charpy impact curves of CLAM (HEAT 0603A).

CLAM was slighter compared with that of JLF-1 after low dose neutron irradiation.

4. Conclusions

Tensile specimens of HEAT 0408B, HEAT 0408D and HEAT 0603A and Charpy specimens of HEAT 0603A were irradiated at 250 °C to 0.02 dpa. Hardening and embrittlement of CLAM occurred after irradiation:

(1) The ultimate strength and yield stress of HEAT 0603A increased 10–30 MPa and total elongation decreased about 4%.
(2) The DBTT shift of CLAM HEAT 0603A, obtained at half the difference between the upper-shelf energy and lower-shelf energy, is about 5 °C.
(3) For CLAM heats 0408B and 0408D, ultimate strength and yield stress increased about 80–150 MPa.

Acknowledgements

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