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PRESSURE VESSEL ANNEALING FOR PLANT LIFE MANAGEMENT (PLM); TENSILE AND HARDNESS PROPERTIES OF IRRADIATED, ANNEALED AND RE-IRRADIATED LOW ALLOY STEEL

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ABSTRACT

Room and higher temperature tensile properties of an irradiated (I) and irradiated-annealed-reirradiated (IAR) pressure vessel (PV) steel are presented. Spectrum tailored pressurized light water reactor (PWR) irradiation at 290°C by fast neutrons up to nominal fluences of $5x10^{19}$ /cm^2 in a swimming pool type reactor caused the tensile yield stress and tensile strength to increase.

The response to an intermediate annealing treatment using 460°C x 18 h, when 50% of the target fluence had been reached and then irradiating to the end fluence (IAR condition) was monitored using hardness measurements and measuring the mechanical properties. Annealing was beneficial in mitigating hardening or embrittlement effects. The rate of re–embrittlement after annealing and re–irradiating was no faster than when no annealing had been performed. Annealing temperatures below 420°C were seen to require excessively long times i.e. $\geq$ 168 h to achieve a reduction in radiation induced hardness for example.

The benefit of a PV annealing treatment has been demonstrated on a laboratory scale, and it is therefore indicated as being a useful tool in the overall strategy for PLM options.

KEYWORDS: Neutron embrittlement, Annealing, Pressure Vessel Steel, Plant Life Management, Mechanical Properties.

1 INTRODUCTION

As nuclear power plants (NPP) become older and approach their nominal end of life (EOL) and orders for new plants do not keep up with the potential loss of electricity production, it is essential to manage the existing plants in order to maintain the delivery of energy at the highest levels of safety. If a deterioration in the mechanical properties of the pressure vessel (PV) (due to neutron irradiation) is solely governing the overall life of the NPP then it is possible to reduce the rate of neutron fluence accumulation by adjusting the fuel bundle configuration for example. Annealing the PV may also be a way to achieve PLM goals due to regenerating mechanical properties affected by neutron irradiation. The following work briefly describes how the annealing parameters of time and temperature can be selected to obtain recovery in mechanical properties. Information is provided which indicates that for these experiments, material and conditions, the rate of re–hardening (or embrittlement) after annealing and re–irradiating was no faster than when no annealing had been performed.

2 EXPERIMENTAL PROCEDURES

2.1 Material

The rolled plate of mock–up low alloy ferritic PV steel (similar to A 533–B) was normalized at 900°C quenched at 880°C tempered at 665°C for 12 h and finally stress relieved at 620°C for 40 h. Due to the intentionally selected high copper content of 0.14 weight % and a nickel content of 0.84 weight %, this 0.18 weight % carbon PV steel can be placed into the category of being radiation sensitive.

2.2 Irradiation

The specimens were loaded into instrumented stainless steel capsules and placed in a swimming pool type materials testing reactor (MTR) where they received a neutron spectrum similar to that in a pressurized water reactor (PWR) at a flux rate of about $5\text{x}10^{12}/\text{cm}^2/\text{s}$. Nominal fluences up to $5\text{x}10^{19}/\text{cm}^2$ were accumulated at 290°C. It should be noted that all fluences quoted hereafter are those neutrons having an energy $\geq$ 1 MeV. Dosimetric fluences were obtained from iron, nickel, niobium and copper monitors which were incorporated in the capsules. The temperature (± 5 °C) was achieved by gamma heating and controlled using a helium-nitrogen gas gap. Some experiments were done by allowing the specimens to accumulate approximately 50% of their foreseen target fluences and then applying a heat treatment (460°C x 18h) to them whilst still in the capsule. The heat treatment had been determined previously using isochronal and isothermal hardness response analysis (see under section, 2.3). After heat treatment, the specimens were re–irradiated to the required fluence targets, giving the IAR condition. This enabled an assessment of the rate of re–hardening (embrittlement) after annealing which is an important aspect for the practical case.

2.3 Determination of Annealing Parameters

A series of 30 min isochronal runs on material irradiated to a fluence of $2.23\text{x}10^{19}/\text{cm}^2$ were performed. Only at temperatures $\geq$400°C did the Vickers' microhardness (HV0.2) begin to recover; by 500°C the hardness was fully back to the unirradiated (U) value. Correspondingly, a series of isothermal runs were performed between 440°C and 500°C and a treatment of 460°C x 18 h was selected because it caused over 90% relative recovery in the microhardness in a fairly practical time.

2.4 Tensile testing

A servohydraulic machine installed in a Hot Cell was used in the extension controlled mode; the strain rate on the specimens was $6 \text{ x } 10^{-6}$ /s. For temperatures higher than ambient, electric heaters were used assuring an accuracy of ± 5°C. The tensile specimens (taken from standard Charpy size blanks) had their axes parallel to the rolling direction in the original block of material.

3 RESULTS AND DISCUSSION

3.1 Tensile and Charpy properties

The absolute changes in tensile yield stress and strength data for the I and IAR conditions at 20°C, 150°C and 300°C as a function of neutron fluence are presented in Figures 1 to 3 respectively. The benefit of annealing at 460°C for 18 h at 50% of the target fluence is evident in that the IAR data exhibit less relative change in property compared to the data obtained for the I condition. The rate of re–hardening for IAR and for all test temperatures investigated appears to be no more than that observed for the I material state. This information is of importance for utilities which are considering the annealing option for PLM because an accelerated embrittlement after annealing is obviously not tolerable. The tensile yield stress and strength behaviour follow the same general pattern of hardening and embrittlement and mitigation for each of the test temperatures used.

It should be noted that beneficial effects were also found for the Charpy notch ductility (toughness) properties which are not fully reported on here. However, the 41 J and 68 J ductile to brittle transition temperature shifts were reduced from typically 90°C to 60°C. Likewise, the upper shelf energies were restored from 146 J to about 175 J i.e. approaching the unirradiated value of 200 J. (N.B. Data refer to a fluence of 5×10^{19} /cm^2.)

3.2 General comments concerned with PV heat treatments for PLM.

A practical point is that a non–optimal heat treatment may not cause enough mechanical property recovery to economically justify the operation; the costs must be balanced against the potential time gained for continued electricity production. If copper precipitates are known to be mostly responsible for the embrittlement, as in the case for this generic type of steel, see for example (1) then annealing is indicated. However, a further aspect is that secondary undesirable effects related to temper embrittlement could be favoured due to the segregation of phosphorus to grain boundaries for example.

This possible mechanism must be taken into consideration when assessing annealing options for relatively high phosphorus ($\geq$ 0.010 weight %) containing materials for example. Attention should also be given to the possible effects of ageing mechanisms which may also contribute a part towards the loss of mechanical properties. Ageing may even affect the amount of recovery in properties achieved by a selected heat treatment. The use of excessively high temperatures ($\geq$500°C) should generally be avoided since microstructural changes could occur and also excessive thermal expansion effects could create additional plant–specific problems.

4 CONCLUSIONS

- Irradiation caused hardening and embrittlement phenomena in the mock–up PV steel. Increases in the hardness, tensile yield stress and strength properties were found. The Charpy toughness was also affected, leading to shifts in the DBTT and losses in USE.

- Annealing, in this case, when approximately 50% of the target fluence had been reached, caused measureable improvement to the mechanical property changes compared to the non–annealed condition.

- A temperature of 460°C for 18 h was found to be a viable combination. The annealing option for an actual PLM strategy should be implemented however, well before 50% of the foreseen EOL fluence is reached.

- The rate of re–hardening and embrittlement after irradiating, annealing and re–irradiating (IAR – condition) was no faster than the embrittlement rate noted for the I condition.

- Temperatures below 440°C require relatively longer times for the recovery of hardness and other mechanical properties whilst temperatures above 500°C are not practicable and may even cause material degradation in their own right.

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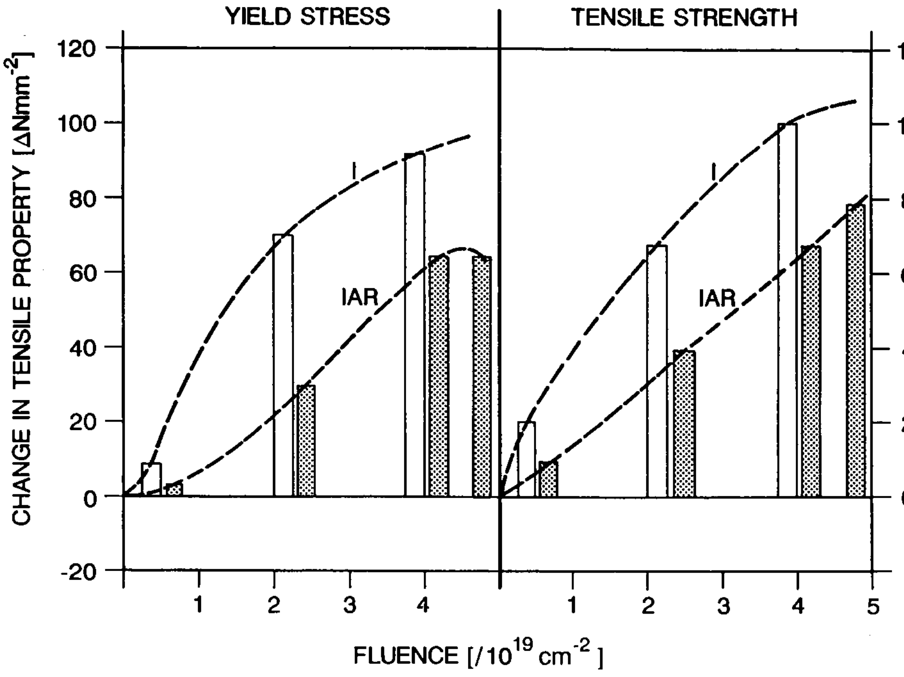

Figure 1: Absolute changes in tensile properties at 20°C.

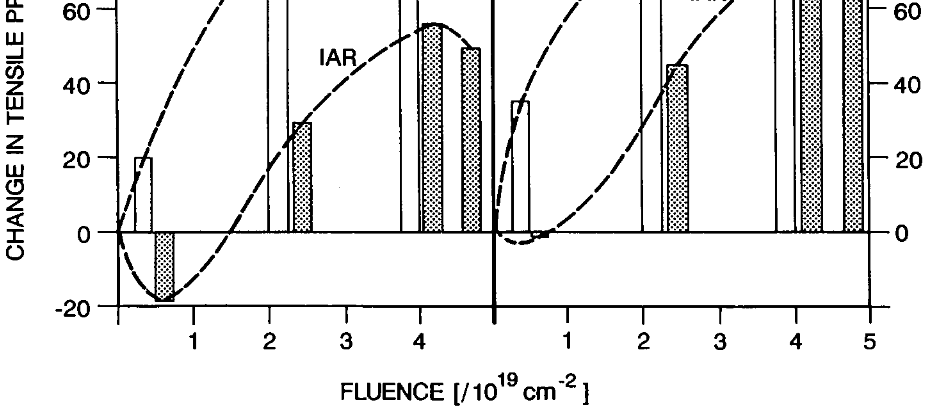

Figure 2: Absolute changes in tensile properties at 150°C.

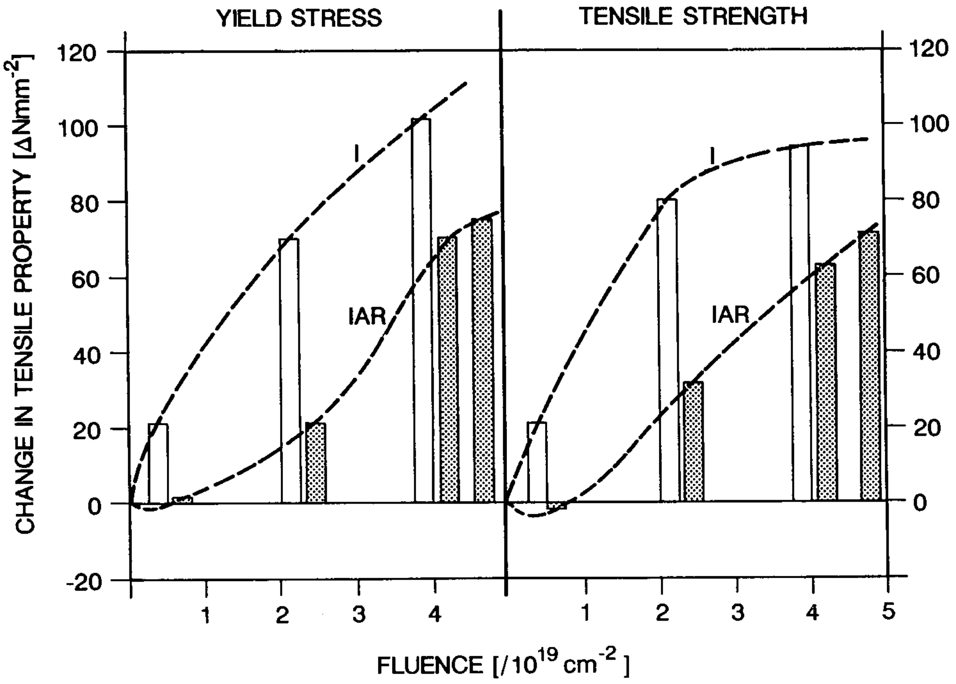

Figure 3: Absolute changes in tensile properties as a function of fast neutron fluence. The testing temperature was 300°C.