Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Effect of Cu on ferritic steels hardening under irradiation

Smetniansky-De Grande, N.
CNEA, Dpto. de Materiales, Buenos Aires, Argentina
Barbu, A.
CEREM, Lab. des Solides Irradiés, Ecole Polytechnique Palaiseau, France

ABSTRACT: It has been shown that a simple model including nucleation, growth and coarsening and assuming that the only effect of irradiation is to enhance Cu diffusion, provides a good description of Cu precipitation kinetics in Fe-Cu model alloys (Smetniansky et al.). To complete this study, in the present work we analyze the incidence of Cu precipitation on material hardness evolution under irradiation, with the help of the Russel and Browns model. Furthermore, by using an empiric relation between the ductile-brittle transition temperature (DBTT) and hardness, the variation of the DBTT component due to Cu precipitation is calculated. Theoretical results are compared with experimental ones.

1 INTRODUCTION

The embrittlement process of Reactor Pressure Vessel (RPV) steels under irradiation is correlated with the microstructural changes responsible for this behavior. It is known that under irradiation mechanical properties change as follows: whereas yield stress and hardness increase, ductility decreases and ductile to brittle transition temperature increases. One of the most important microstructural mechanisms responsible for these changes is the presence of copper in the matrix and the formation of Cu precipitates that block dislocations movement.

To predict the behavior of RPV steels under irradiation conditions, models representing the associated physical process are used. In particular Cu precipitation kinetics, for binary Fe-Cu alloys, is modelled by assuming nucleation, growth and coarsening as the phenomena leading to precipitation evolution, including interaction between precipitates (Smetniansky et al.).

The goal of the present work is to study hardness evolution in Fe-Cu binary alloys under irradiation. The number of precipitates and their mean radius, calculated by means of the above mentioned model, are used to follow yield strength evolution with the help of the model of Russell and Brown. In Section 2 the yield stress evolution calculation is detailed and the empirical relations used to calculate hardness evolution are described; in Section 3 the empirical correlation between radiation hardening and the DBTT shift, due to Cu precipitation, is specified. Finally, in Section 4 results are presented and analyzed.

2 HARDNESS EVOLUTION

The model of Russell and Brown predicts the variation of the material strength due to precipitates by modelling the interaction between matrix slip dislocations and Cu precipitates, of lower shear modulus than the matrix. This strength variation represents the additional tension that must be provided to move a dislocation through an array of precipitates, and is calculated as:

(1)
$$\sigma^P = 2.907\ 10^{-3}\ MPa\ \frac{f^{1/2}}{\bar{r}} \left[1 - \left(\frac{E_1}{E_2} \right)^2 \right]^{3/4}$$

being E_1 and E_2 the dislocation energy in the precipitate and in the matrix, respectively, with $E_1 < E_2$; $\bar{r}$ is the precipitate mean radius and f is the volume fraction of precipitates. The number of precipitates and their mean radius are calculated by means of the model developed by Smetniansky et al.

Furthermore, the expression for E_1/E_2 is given as (Russell and Brown):

(2)
$$\frac{E_1}{E_2} = 0.2\ \log\frac{\bar{r}}{6.2} + \frac{1}{3}\ \log\frac{6200}{\bar{r}}$$

The total tensile stress is represented by the matrix strength σ^0, plus the strength due to the presence of precipitates:

(3)
$$\sigma = \sigma^0 + \sigma^P$$

As precipitation evolves, the concentration of Cu in the matrix decreases and the matrix strength changes. The calculation of the matrix strength, for a ferrite grain size of 40 μm, as a function of Cu concentration is detailed in the Appendix.

But to compare experimental hardness results with the above calculated tensile stress values, we have to find a relation between hardness and stress. With this purpose and using experimental results of solid solution hardness (Mathon), obtained with Vicker hardness tests under 50 g load and for different concentrations of Cu in the matrix (C_{Cu}), we plot H_v vs C_{Cu}. By extrapolation we obtain the hardness value for pure iron; knowing the corresponding stress value, we arrive to the expression:

(4)
$$\sigma = 2H_v$$

This linear relation does not depend on the concentration of Cu in the matrix.

Finally, applying eqn.(4) to the values calculated with eqn.(3), we obtain theoretical hardness values as a function of time, temperature and Cu concentration in the solid solution.

3 DUCTILE-BRITTLE TRANSITION TEMPERATURE SHIFT

Finally, to calculate the variation of the ductile-brittle transition temperature, we use the irradiation shift/hardness correlation presented by English et.al., based on experimental results of Williams et al. for plate low alloy steels after irradiation. This relation is represented by the expression:

$$\Delta T_{41J} = 1.64\ \Delta H_v \tag{5}$$

being ΔH_v the hardness variation of the irradiated material with respect to the unirradiated one and ΔT_{41J} the equivalent DBTT shift. Results are detailed in the next Section.

4 RESULTS AND DISCUSSION

Calculations have been performed for Fe-Cu containing an initial Cu concentration of 1.34%at., irradiated at 300°C. Irradiation experiences have been made with a Van de Graff accelerator, with electron fluxes of 3.7×10^{13} $e^-/cm^2.s$ which correspond to a point defect creation rate of 2×10^{-9}dpa/s.

The calculated values of hardness are plotted in Fig.1 as a function of time. Under irradiation conditions, copper precipitation is enhanced due to radiation enhanced diffusion, as a consequence of vacancy supersaturation. We verify that the time to peak hardness depends on temperature and dose rate. On the other hand the maximum hardness value depends on the initial concentration of Cu in the matrix.

The corresponding hardness experimental results obtained with Vicker tests are included in Fig.1. As can be seen, theoretical results follow the same tendency as experimental ones. This conclusion is valid only if we consider in the calculations that precipitate nuclei are present at the beginning and no further nucleation is allowed.

It is worthy of note that as precipitation evolves, Cu precipitates change from coherent bcc to incoherent fcc clusters, for precipitates of about 9nm diameter (Russell and Brown). But in the calculations we use fcc copper elastic properties because the bcc ones are not known.

The final step in modelling is to transform hardening into the equivalent temperature shift, using an empirical correlation. With the aim of calculating this temperature shift, we apply eqn.(5) to the hardness calculated values and we obtain the DBTT shift due to irradiation. In Fig.2 we plot ΔDBTT vs damage dose (in dpa). The transition shift

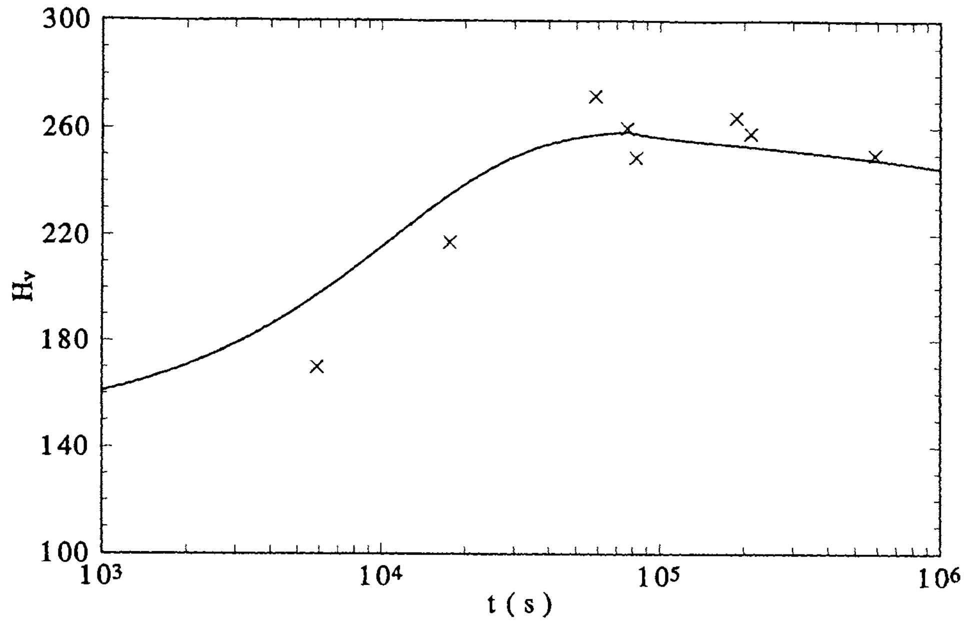

Figure 1. H_v as a function of t at 300°C, under irradiation. Symbols represent experimental results and lines theoretical predictions.

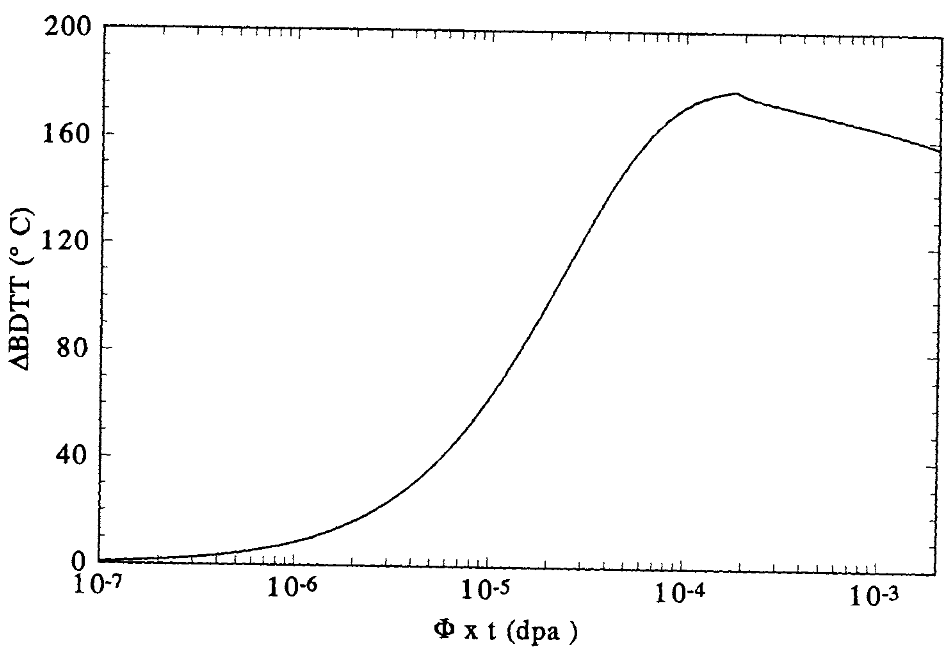

Figure 2. Theoretical predicted values of the variation of the ductil-brittle transition temperature as a function of the dose (in dpa).

reaches a maximum around $2x10^{-4}$ dpa and then decreases. That means that at low doses, copper precipitation controls embrittlement. These results accord with the ones of English et al. For high dose values, other physical phenomena have to be included in the model.

5 CONCLUSIONS

In conclusion, a simple model that takes into account only growth and coarsening of precipitates, together with a model that predicts material hardness changes due to precipitates, assumed as attractive obstacles, follow experimental results of hardness obtained with Vicker tests.

It is important to remark that only at low doses Cu precipitation controls embrittlement.

ACKNOWLEDGMENT

One of the authors, N.Smetniansky-De Grande, wishes to thank the 'Proyecto Multinacional de Tecnología de Materiales' OEA-CNEA, of the Organization of American States, for partially supporting this work.

REFERENCES

English C.A., Fudge A.J., McElroy R.J., Phytian W.J., Buswell J.T., Bolton C.J., Heffer P.J.H., Jones R.B. and Williams T.J. 1993. Approach and methodology for condition assessment of thermal reactor pressure vessels. *Int. J. Pres. Ves. & Piping* 54:49-88

Mathon M.H.. 1995. Thesis to be presented at the Univ. Paris XI, France

Russell Kathryn C. and Brown L.M. 1972. A dispersion strengthening model based on differing elastic moduli applied to the iron-copper system. *Acta Met.* Vol 20:969-974

Smetniansky-De Grande N. and Barbu A. 1994. Study of Cu precipitation mechanisms in Fe-Cu 1.34% at. alloy under electron irradiation. *Radiation Effects and Defects in Solids* Vol.132:157-167

Williams T.J., Ellis D., Swan D.I., McGuire J., Walley S.P., English C.A., Venables J.H. and Ray P.H.N. 1986. Proc. 2nd Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors. Sept. 1985

APPENDIX

MATRIX STRENGTH

Applying eqn.(4) to the experimental hardness results of different solid solutions, we obtain the corresponding matrix strength results (σ^0) as a function of Cu concentration in the matrix. We plot σ^0 vs C_{Cu} and we obtain the linear relation:

$$\sigma^0 \ (MPa) = 156 + 7020 \ C_{Cu}$$

where σ^0 is given in MPa and C_{Cu} in atomic per cent.