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Effect of irradiation temperature and dose on SHC of pure Cu

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A B S T R A C T

Radiation hardening of pure copper is sufficiently well investigated. At the same time, such important problem as the effect of neutron irradiation on strain-hardening coefficient (SHC) of pure Cu and copper alloys is poorly investigated, though these data are important for calculation of stress-strained state of the ITER components. This paper presents the results of investigation into the effect of neutron irradiation temperature and dose on SHC of pure Cu. The results of processing of true stress–strain curves of pure Cu shows that under neutron irradiation in the range of 80–200 °C SHC decreases monotonously with increase in irradiation dose. The conclusion is made that degradation in SHC under irradiation for copper alloys should be taken into account during the stress analysis of ITER components.

1. Introduction

The investigations of radiation hardening and embrittlement of materials are usually focused on the irradiation effect on the yield strength and uniform elongation. Yet, the effect of neutron irradiation on the strain-hardening coefficient (SHC) is investigated but poorly. On the whole, it is known [1–3] that low-temperature neutron irradiation ($T_{irr} < 0.3T_{melting}$) causes the SHC of irradiated metals to drop, as demonstrated by a decrease in the hardening rate observed on the stress–strain curves of irradiated samples.

But, the quantitative estimates of the neutron irradiation effect on SHC are practically lacking in the literature. During the stress analysis of the ITER components, designers use usually the SHC value, which is rather roughly extrapolated from the slope of stress–strain curves. Therefore, it is of importance to obtain exact values of the SHC. The large bulk of digital stress–strain curves on the properties of irradiated pure copper and copper alloys obtained by the Russian Federation Participants Team in the framework of the ITER activities make it possible to estimate quantitatively the effect of irradiation dose and temperature on the SHC of copper based alloys. An attempt of such an investigation is presented in the report.

2. Experimental procedure

In this study, the stress–strain curves obtained for pure copper (pure Cu 99.997%) samples were processed. The samples were irradiated on the RBT-6 reactor. The report presents the results of the latest two experiments made at T_{irr} = 200 °C and 300 °C. The data on the previous experiments made at T_{irr} = 80 °C and 150 °C [4,5] were also processed.

The following methodology was used as the basis for calculation of the SHC by the true stress–strain curves:

In a number of cases the designers need full true stress–strain curves [6,7]. We have recalculated the available engineering stress–strain curves into the true stress–strain curves and analyzed possible ways of calculating the true stress–strain curves.

The following phenomenological approach is offered in order to assess the stresses.

The dependence of true stress versus deformation is determined by the equation:

$$\sigma = \mathbf{a} * (\varepsilon_{\mathbf{plastic}})^{\mathbf{m}} + \mathbf{b} \tag{1}$$

here stresses and deformations are true.

The elastic portion of strain can be simply determined by the Hook's law. The plastic portion of strain is offered to be calculated on the basis of processing of the stress–strain curves.

It is offered to perform the following calculations using database on pure Cu and CuCrZr IG alloy [4,5,8,9], in particular, the engineering stress–strain curves of pure Cu in unirradiated condition and after neutron irradiation.

The methodology of calculations [4] included the following steps. The digital data sets obtained from tests in values strength vs. strain (~4000 × 2 points) were used to build digital arrays of true stress vs. true plastic strain. Then these arrays were processed on the method of non-linear regression to obtain parameters **m**, **a**, **b** in the Eq. (1). True strain and true stress are determined as:

$$\varepsilon_{true} = \ln(1 + \varepsilon_{eng}) \quad \sigma_{true} = \sigma_{eng} * (1 + \varepsilon_{eng}).$$

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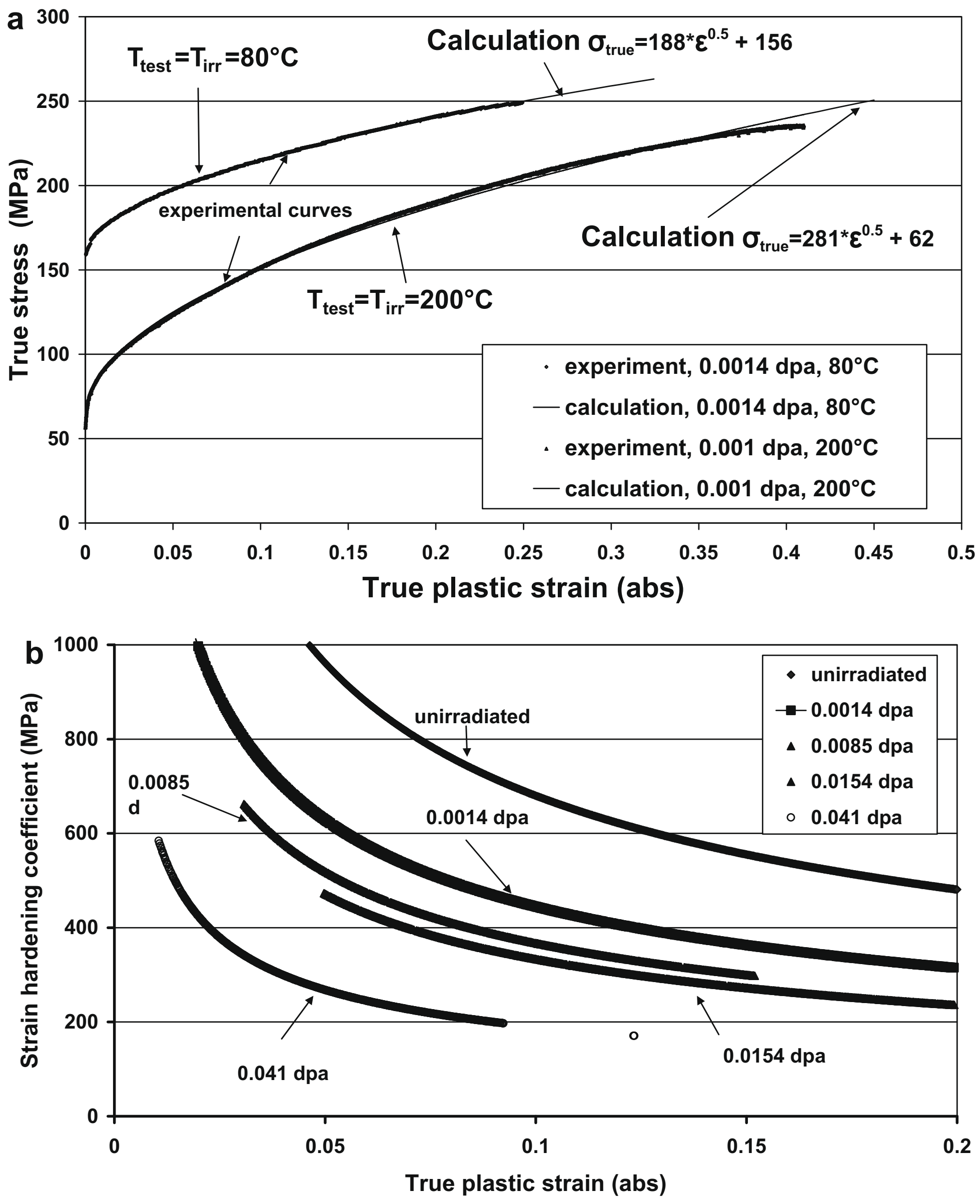

Fig. 1. Experimental true stress–strain curves for pure Cu, irradiated in RBT-6 rector to a dose of 0.0014 dpa, $T_{test} = T_{irr} = 80$ °C and 0.0011 dpa, $T_{test} = T_{irr} = 200$ °C and calculated by formula (2) stress–train curves (a); effect of damage dose on SHC of pure Cu irradiated in RBT-6 rector in dose range 0.0014–0.041 dpa, $T_{test} = T_{irr} = 80$ °C (b).

The analysis the data of Cu and CuCrZr IG alloy showed that the best reproduction of curves and their correspondence to experimental data are obtained at **m = 0.5.**

$$\sigma_{\mathbf{true}} = \mathbf{a} * (\varepsilon_{\mathbf{plastic\ true}})^{\mathbf{0.5}} + \mathbf{b} \quad (2)$$

Fig. 1(a) demonstrates the efficiency of the proposed method for pure Cu irradiated to a dose of 0.001 dpa at $T_{test} = T_{irr} = 80$ °C and $T_{test} = T_{irr} = 200$ °C. Fig. 1(a) presents the experimental true curves for pure Cu samples after neutron irradiation at 80 °C and 200 °C to doses of $\sim 10^{-3}$ dpa. The calculated curves, for construction of which the coefficients **a** and **b** obtained from formula (2) were used, were superimposed on these experimental curves. It is seen that the calculation and experimental curves coincide with a fine precision.

3. Results

Fig. 2 presents the dose dependences of radiation hardening of pure copper at T_{irr} – 80; 150; 200; 300 °C. It is evident that the hardening increases with the irradiation dose. A rise in the irradiation temperature causes the radiation hardening to drop. In particular, at a dose of $\sim 10^{-1}$ dpa the radiation hardening of pure copper at $T_{irr} = 80$ °C amounts to ~200 MPa, and at $T_{irr} = 300$ °C only to ~40 MPa.

Hence, the uniform elongation of pure copper drops with a rise in the dose. An increase in the irradiation temperature increases the uniform elongation of materials.

The value for SHC can be obtained from formula (2):

$$\delta\sigma/\delta\varepsilon = \mathbf{f}(\varepsilon) = (\mathbf{0.5a})\varepsilon^{-\mathbf{0.5}} \quad (3)$$

Fig. 1(b) shows the effect of the neutron irradiation dose on the SHC dependence on the true plastic strain. The SHC values were calculated by formula (3) (based on **a** – value obtained from processing of experimental stress–strain curves). As is seen, the SHC drops with a rise in strain. An increase in the irradiation dose causes the SHC to drop.

As the SHC depends on the deformation at which it is calculated, it seems reasonable to estimate the irradiation effect on

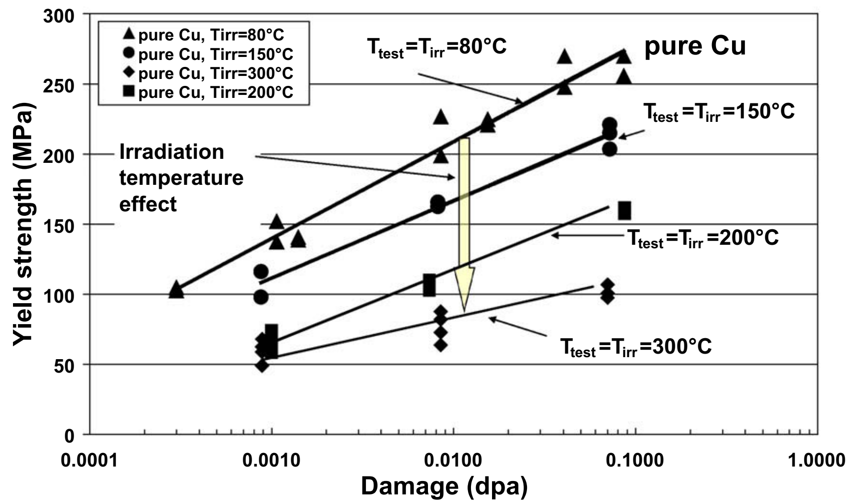

Fig. 2. Effect of irradiation temperature on radiation hardening of pure Cu, $T_{test} = T_{irr}$.

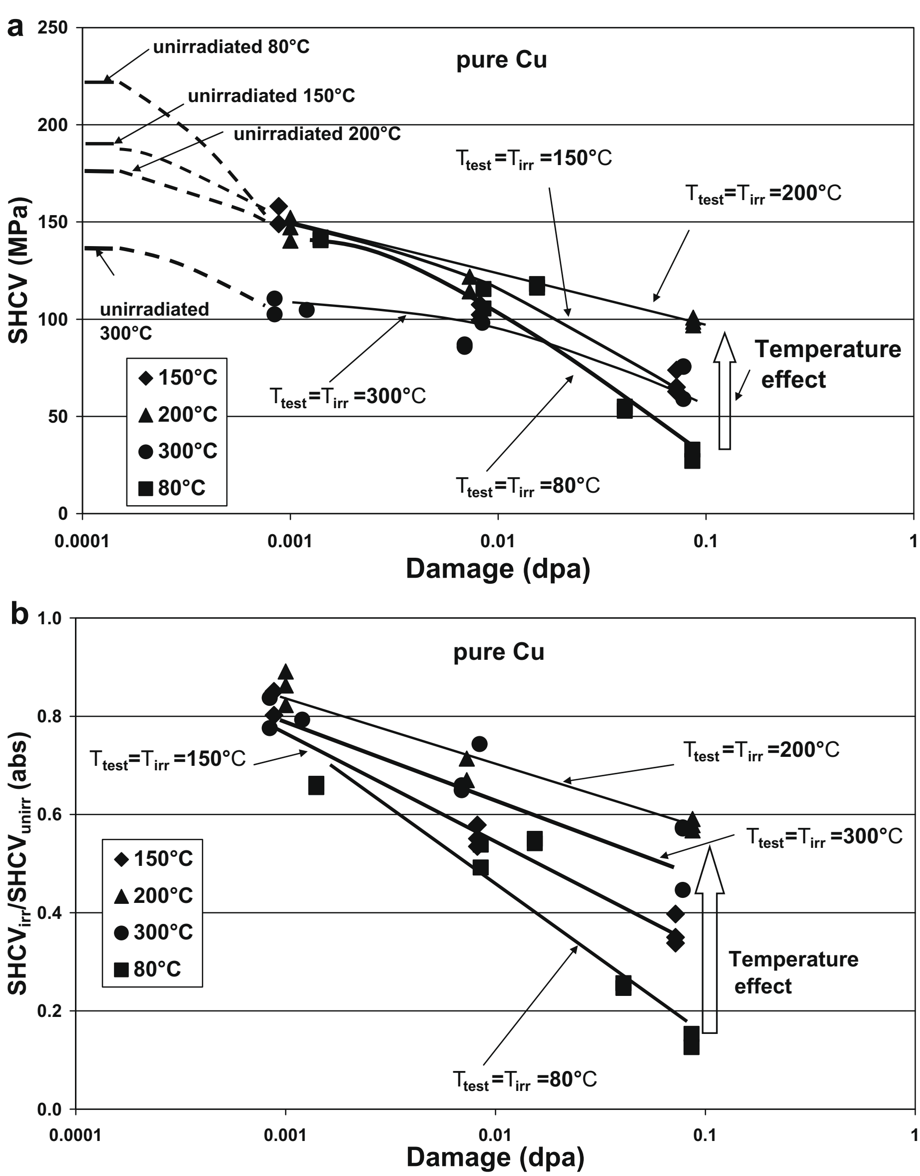

Fig. 3. Effect of damage dose and irradiation temperature on SHCV coefficient (a) and relative value $\gamma = SHCV_{irr}/SHCV_{unirr}$ (b), of pure Cu irradiated in RBT-6 rector in dose range 0.001–0.1 dpa, $T_{test} = T_{irr}$.

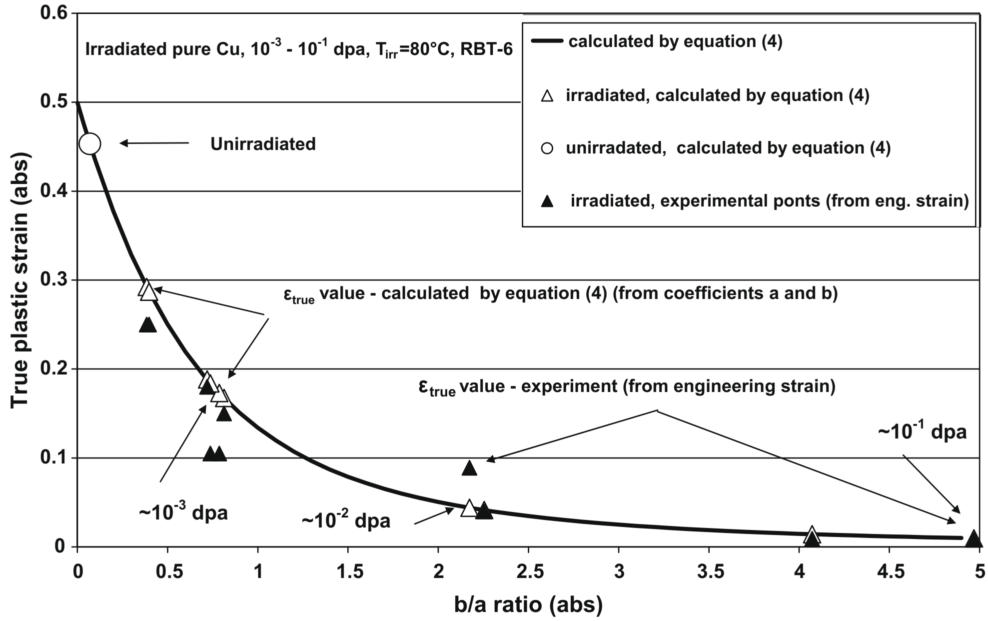

Fig. 4. The true plastic strain versus the parameter **b/a** for pure copper samples irradiated in the RBT-6 reactor in the dose range of 0.001–0.1 dpa at 80 °C. Experimental points – filled symbols; calculated points (formula (4)) – open symbols.

the SHC using a parameter independent of the deformation. Let us select as such a parameter the value 0.5∗**a**, i.e., the coefficient in the formula (3) and call it the SHCV coefficient (strain-hardening coefficient value). As opposed to the SHC, the SHCV does not depend on ε.

Fig. 3(a) presents the dose dependences of the SHCV obtained at irradiation temperatures of 80; 150; 200; 300 °C. It is evident that a rise in the dose causes the SHCV to drop. SHCV increases with the irradiation temperature (in the irradiation (testing) temperature range of 80–200 °C). Though the SHCV level in the initial state at T_{test} = 80, 150, 200 °C is different, the SHCV at 10^{-3} dpa is practically the same for all three irradiation temperatures. At higher irradiation doses the SHCV decreases. And in this case the SHCV decrease is maximum at T_{irr} = 80 °C and minimum at 200 °C.

At T_{irr} = 300 °C pure copper and copper alloys, when tested, are in the hardening–softening regime due to thermo activation processes participating in the deformation process [10]. Therefore, the initial level of the SHCV decreases essentially at T_{test} = 300 °C and after irradiation at 300 °C the SHCV drops but with a low rate.

4. Discussions

In order to correctly estimate the effect of the irradiation dose and temperature on the SHCV, the relative value $\gamma = \mathrm{SHCV}_{irr}/\mathrm{SHCV}_{unirr}$ should be used, making it possible to eliminate the effect of the differences in the initial level of SHCV_{unirr} on the dose dependences.

Fig. 3(b) presents the dose dependences of γ at four irradiation temperatures, i.e., 80, 150, 200 and 300 °C. As is seen, γ drops with a rise in the irradiation dose and a decrease in the irradiation temperature. The difference in γ for different radiation temperatures is minimal at a low dose of $\sim10^{-3}$ dpa and maximal at a dose of 10^{-1} dpa. The values of γ for T_{irr} = 300 °C are close to those at T_{irr} = 200 °C.

The approach developed makes it possible to calculate the uniform elongation of materials using the coefficients **a** and **b** obtained by processing the stress–strain curves (**a** – corresponding to the SHC values and **b** – to the yield strength).

Actually, from the criterion of losses in the deformation stability

$$\delta\sigma/\delta\varepsilon = \sigma,$$

it follows that $\delta\sigma/\delta\varepsilon = \mathbf{f}(\varepsilon) = (\mathbf{0.5a})\varepsilon^{-\mathbf{0.5}} = \mathbf{a} * (\varepsilon)^{\mathbf{0.5}} + \mathbf{b}$, and solving the quadratic equation relative to $(\varepsilon)^{0.5}$ we obtain:

$$\varepsilon_{\text{true uniform}} = (-\mathbf{b}/2\mathbf{a} + (\mathbf{b}^2/4\mathbf{a}^2 + 0.5)^{0.5})^2 \quad (4)$$

The analysis of formula (4) reveals that the uniform elongation value is found by the ratio **b/a**, i.e. by the ratio of the yield strength to the strain-hardening coefficient. In the unirradiated state, the yield strength of pure copper is low, and the SHC value is high, hence $\mathbf{b}/\mathbf{a} \ll \mathbf{0.5}$, and by formula (4) we obtain $\varepsilon_{\text{true uniform}} \to 0.5$. For irradiated pure copper the yield strength of pure copper (**b**) increases by a factor of three–five, and the SHC value (**a**) decreases, hence, $\mathbf{b}/\mathbf{a} \gg \mathbf{0.5}$, and by formula (4) we obtain $\varepsilon_{\text{true uniform}} \to 0$. Thus, formula (4) describes correctly qualitatively a change in the uniform elongation under irradiation.

Fig. 4 presents the true plastic strain versus the parameter **b/a** for pure copper samples irradiated in the RBT-6 reactor at 80 °C. It is seen that the calculated by formula (4) values of the true plastic strain agree well with the experimentally obtained values of $\varepsilon_{true} = \ln(1 + \varepsilon_{eng})$.

Thus, the proposed method for data processing makes it possible to generalize the behavior of individual samples, to obtain the averaged calculated true strain–stress curves. With an adequate database of such curves at different irradiation temperatures and doses it is possible to construct analytical dependences of the parameters **a** and **b** on the dose (D) and irradiation temperature (T).

$$\mathbf{a} = f_1(\mathrm{D},T);\ \mathbf{b} = f_2(\mathrm{D},T) \quad (5)$$

Formula (5) can be used to obtain the true digital strain–stress curves at any irradiation temperature and dose.

5. Conclusions

The studies performed have made it possible to establish the main regularities in the SHC behavior of pure copper under irradiation. It has been demonstrated that at T_{irr} = 80–200 °C the SHC of pure copper drops monotonously with the irradiation dose and increases with the irradiation temperature.

The regularities of the behavior of the parameters **a** and **b** under irradiation make it possible to extrapolate these parameters for intermediate irradiation doses and temperatures.

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