DEVELOPMENT OF SUPERPOSITION RULES FOR HARDENING IN ALLOYS CONTAINING MULTIPLE DEFECT POPULATIONS — G. R. Odette, G. E. Lucas and G. Tedeski, and B. D. Wirth (University of California, Santa Barbara)

OBJECTIVE

The objective of this work is to develop a superpositiuon law to assess the net contribution of two defect population to hardening.

SUMMARY

In this study extensive computer simulations were carried out to calculate the yield strengths arising from the presence of two defect populations. The motion of an individual dislocation through a random obstacle field containing varying ratios of obstacles with two different barrier strengths (strong and weak) was computed based on equilibrium bowing of dislocation segments between adjacent obstacles. Yield stress was determined as the minimum stress necessary for the dislocation to successfully traverse the obstacle field. The results show that the superposition law is neither linear nor root sum square, but can be approximately represented by a superposition weighting parameter that is a simple analytical function of the individual strong and weak barrier strengths. Illustrations of the implications of this law are provided.

PROGRESS AND STATUS

Introduction

Radiation hardening in structural materials in general, and in fusion reactor materials in particular, can arise from the evolution of more than one defect type. Numerous studies have shown that the contributions to hardening from a single defect type can be reasonably predicted by simple barrier hardening models, [1-8] where the yield stress contribution produced by dispersed obstacles, σ_o, is given by

$$\sigma_O = M\alpha' Gb\sqrt{N_O} \tag{1}$$

where N_o = areal density of obstacles, b is the Burgers vector of the dislocation moving in the obstacle field, M is the Taylor factor (~3), G is the shear modulus, and α' is an effective barrier strength for the obstacle type and field. Note that the morphology of a dislocation in the obstacle field results in an effective strength α' which is smaller than the individual obstacle strength α, where $0 < \alpha < 1$; i.e., $\alpha' < \alpha$.

The total yield stress σ_t from two types of obstacles (σ_1, α_1 and σ_2, α_2) falls between a linear sum (LS) and a root-sum square (RSS) limit, and it can be expressed in terms of a superposition parameter S given by

$$\sigma_t = S(\sigma_1^2 + \sigma_2^2) + (1-S)\sqrt{\sigma_1^2 + \sigma_2^2} \tag{2}$$

Hence, S=1 corresponds to LS superposition and S=0 corresponds to RSS. In general, the value of S lies in between; i.e., 0 < S < 1. The magnitude of S has a significant impact on not only hardening but post-irradiation annealing (PIA). For instance, consider the addition of an irradiation defect strength contribution of $\sigma_2 = 200$ MPa to a material with a pre-existing population of defects which impart a strength of $\sigma_1 = 200$ MPa. The irradiation hardening $\Delta\sigma_t$ would be the full 200 (i.e., 200 + 200 - 200) MPa for LS superposition (S=1) compared to $\Delta\sigma_t = 82$ MPa ($\sqrt{200^2 + 200^2} - 200$) for RSS (S=0); and for an intermediate value of S, say S=0.5, an intermediate value of $\Delta\sigma_t = 141$MPa would obtain. If after PIA, the value of σ_2 were reduced to 100 MPa by recovery, LS superposition would lead to a 50% recovery, and RSS a 71%. If PIA also altered S, an additional component of recovery would obtain; for example, if S were to decrease from 0.5 to 0 in this same example, the recovery would increase to 83%.

This study was undertaken to investigate this superposition law and develop a simple model for S by using computer simulations to calculate the yields strength for various defect populations.

Computer Simulations

The motion of an individual dislocation through a random obstacle field containing varying ratios of obstacles with two different barrier strengths (strong, α_s, and weak, α_w) was computed based on equilibrium bowing of dislocation segments between adjacent obstacles, using the methods pioneered by Foreman and Makin. [9]

Figure 1 illustrates various characteristics of the calculational results. For a dislocation passing through a field of weak obstacles, the dislocation remains fairly linear. When it passes through a field of strong obstacles, it bows significantly between adjacent particles before surmounting the obstacle, and the effective linear obstacle density along the dislocation line increases accordingly. In a mixed filed the dislocation is bowed between strong obstacles, but the front is only slightly perturbed by the weaker obstacles in between. The yield stress in all cases is taken as the value of applied stress when the dislocation successfully passes through the obstacle field.

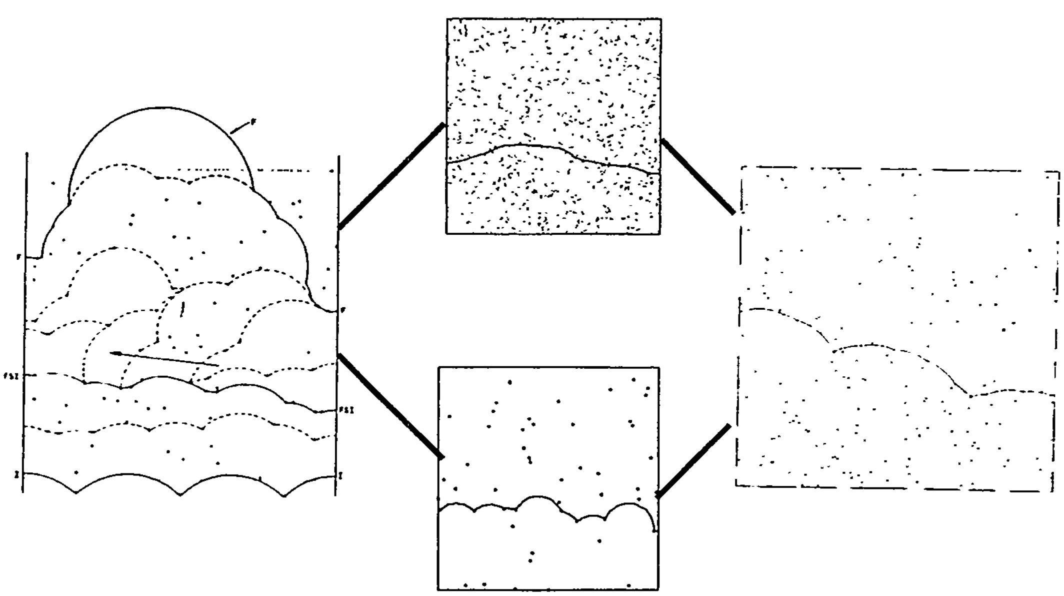

Figure 1. Illustration of dislocation moving through obstacle fields in computer simulations.

Results

It was found that obstacles with similar barrier strengths obey a RSS type of superposition law, with S=0. However, a mix of weak obstacles (α_w) and strong obstacles (α_s) was found to result in an intermediate behavior, with $0 < S < 1$, and S increasing as α_w decreases and α_s increases as

$$S \sim \alpha_s - \alpha_w (4.3 - 2.4\, \alpha_s) \quad (3)$$

This is illustrated in Figure 2 which compares the values of S obtained from the computer simulations with that calculated from eqn (3). There was a relatively weak dependence observed on the relative concentrations of strong and weak obstacles.

The consequence of this is that the contribution of a defect to hardening can depend strongly on the relative strength of obstacles to the pre-existing defects. Addition of dissimilar strength barriers results in more significant net hardening per increment of individual barrier strength (approaching LS) than addition of similar barriers (approaching RSS).

APPLICATION

This effect can be illustrated for irradiation hardening in reactor pressure vessel (RPV) steels. The initial strength in these steels is strongly affected by the presence of an array of strong barriers (Mo_2C) with an estimated α_s of 0.9 giving rise to a strengthening contribution of about σ_c ~ 200 MPa. [10] In RPV steels containing significant copper impurity content (Cu > 0.1), irradiation hardening tends to be dominated by the formation of copper rich precipitates (CRPs) which may be alloyed with Ni and Mn, along with the formation of a matrix defect (MDs) population. [11]

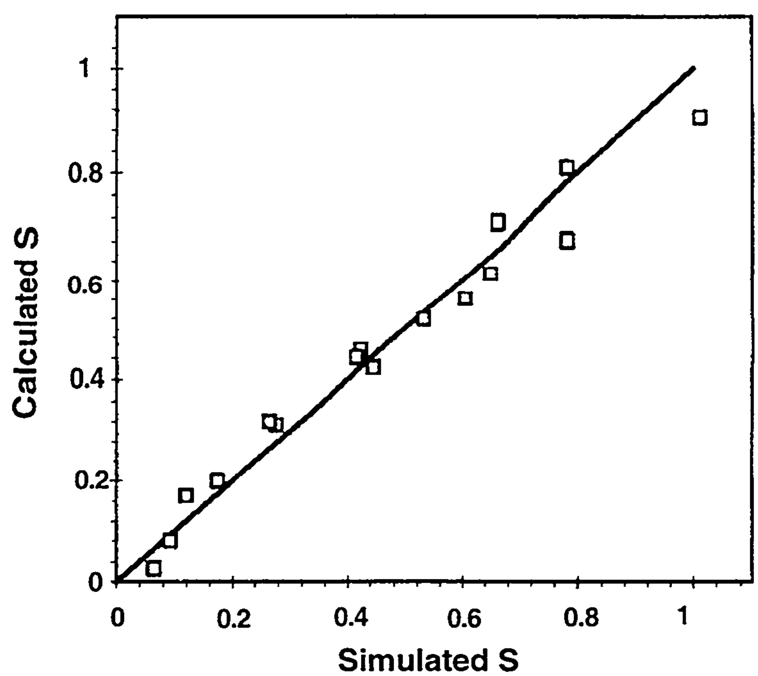

Figure 2. Comparison of calculated values of superposition parameter S with values determined from computer simulations

Similarly, the post-irradiation annealing response is related to changes in these defect populations with time at temperature. The hardening contribution of the CRPs, σ_p, and hence their barrier strength α_p, can be estimated from a Russell-Brown modulus interaction model, [12] along with the knowledge of the size, number density and composition of the precipitates, which can be obtained from small angle neutron scattering (SANS) measurements. [11] The contribution from MDs of the order σ_m (where α_m <<1), can be added in empirically. The total irradiation hardening can be estimated from

$$\Delta\sigma_i = S(\sigma_c + \sigma_p) + (1-S)\sqrt{\sigma_c^2 + \sigma_p^2} - \sigma_c + \sigma_m \qquad (4)$$

Figure 3 shows that predictions of hardening based on microstructural measurements combined with equation (4) are in very good agreement with measured values of yield strength change.

Figure 4 shows the influence of superposition on the post-irradiation annealing (PIA) response. Data points were obtained from microhardness measurements, and the solid lines are predictions of the hardening from application of the Russel-Brown model and the corresponding SANS data combined with the superposition law. [13] Figure 4a corresponds to PIA in a A533B-type model steel containing no Mo (and hence no Mo_2C); hence the hardening and PIA recovery is almost entirely due to the formation and recovery of CRPs and matrix damage (i.e., $\Delta\sigma = \sigma_p + \sigma_m$), and the sluggish coarsening of the CRPs during PIA results in substantial residual hardening even after 1000h at temperature. On the other hand, Figure 4b corresponds to PIA in an A533B-type model steel containing 0.5Mo (and hence Mo_2C). In the as-irradiated condition, the CRPs have a small α_w relative to the strong carbide α_s, and the superposition is between LS and RSS; hence, the total hardening is less than the CRP contribution alone. Upon annealing, MDs anneal out reducing σ_m and CRP dissolution and coarsening reduces both σ_p and S, resulting in significantly higher recovery.

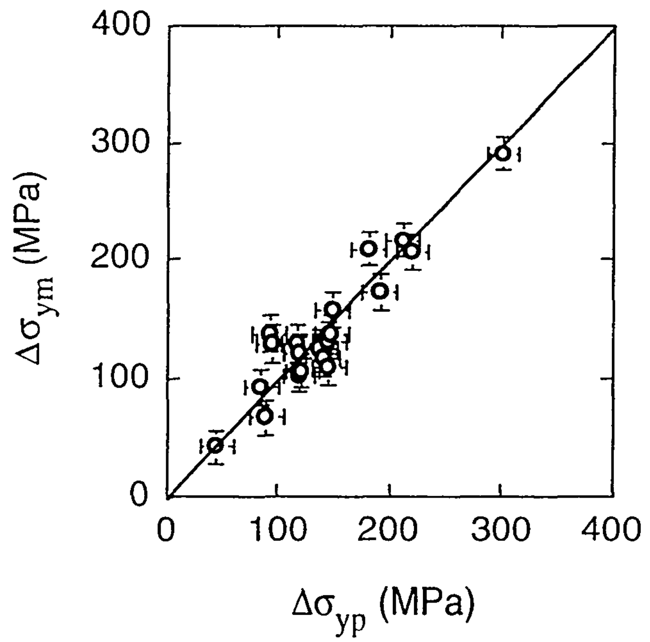

Figure 3. Comparison of measured values of yield stress change with values calculated from microstructural data using the superposition law.

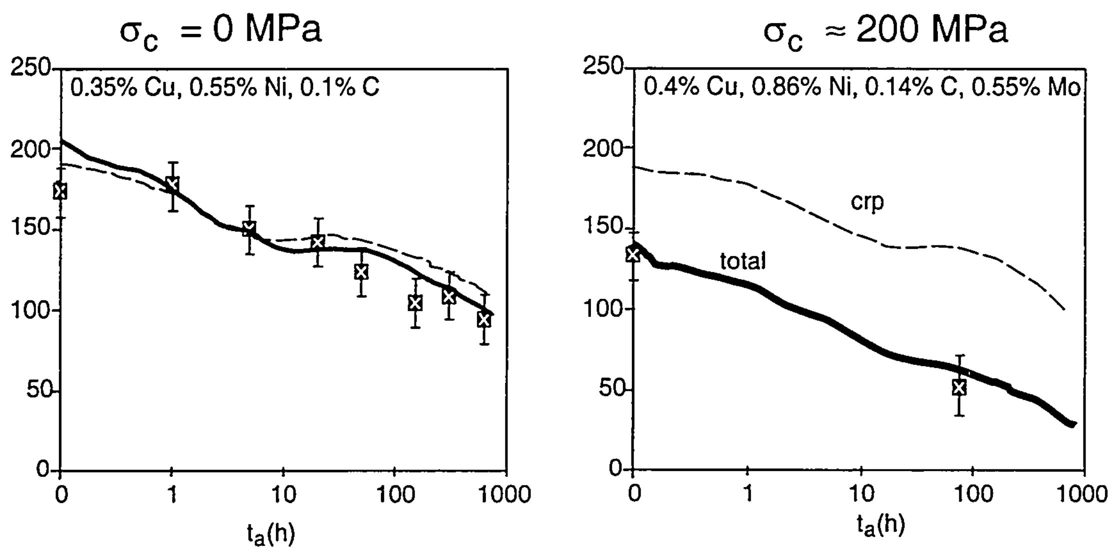

Figure 4. Calculated and measured changes of residual hardening during post-irradiation annealing for A533B-type alloys a) without and b) with Mo additions. In a) the recovery corresponds to the linear superposition of contributions from CRPs and matrix defects (MD). In b) recovery is enhanced by a reduction in σ_m, σ_p and S.

CONCLUSIONS

Computer simulations of dislocations moving in obstacle fields have been used to derive a simple analytical model of the superposition of strengthening from two obstacle types. The superposition model is particularly useful in evaluating changes in strength attributed to the addition (and removal) of a weak(er) obstacle field to (from) a pre-existing strong obstacle field, a situation which is typical for irradiation hardening (and post-irradiation annealing) in structural materials.

ACKNOWLEDGMENTS

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