ON THE RELATION BETWEEN IRRADIATION INDUCED CHANGES IN THE MASTER CURVE REFERENCE TEMPERATURE SHIFT AND CHANGES IN STRAIN HARDENED FLOW STRESS—G. R. Odette, M. Y. He, and T. Yamamoto (University of California, Santa Barbara)

OBJECTIVE

Relation between irradiation induced changes in the master curve reference temperature shift and changes in strain hardened flow.

SUMMARY

Irradiation hardening produces increases in the cleavage transition fracture toughness reference temperature (ΔT_o). It is traditional to relate ΔT_o to the corresponding changes in the yield stress, $\Delta\sigma_y$, as $C_o = \Delta T_o/\Delta\sigma_y$. However, it is a strain-hardened flow stress, σ_{fl}, in the fracture process zone that controls cleavage, rather than σ_y. Thus, irradiation induced decreases in the strain hardening $\Delta\sigma_{sh}$ (< 0) must be considered along with $\Delta\sigma_y$(> 0) in evaluating ΔT_o. The $\Delta\sigma_{sh}$ in reactor pressure vessel (RPV) steels irradiated to low doses at around 300°C are small, even for large $\Delta\sigma_y$. However, the $\Delta\sigma_{sh}$ are much greater for high dose irradiations of tempered martensitic steels (TMS) that are candidates for fusion applications. As a result, for the TMS case the C_o are less, and in some instances much less, than for RPV steels and irradiation conditions. We address two key questions. First, how does $\Delta\sigma_{sh}$ influence the $C_o = \Delta T_o/\Delta\sigma_y$ relation? Second, is it possible to derive a universal relation between ΔT_o and $\Delta\sigma_{fl}$ averaged over a pertinent range of ε, $<\Delta\sigma_{fl}>$, such that a $C_{o'} = \Delta T_o/<\Delta\sigma_{fl}>$ is independent of the individual values of $\Delta\sigma_y$ and $\Delta\sigma_{sh}$? The results of this study suggest that $<\Delta\sigma_{fl}>$ averaged between 0 and 0.1 provides a similar $C_{o'}$ for various assumptions about the effect of irradiation on $\Delta\sigma_{sh}$. Notably, changes in indentation hardness, ΔH, are also directly related to this same $<\Delta\sigma_{fl}>$. Hence, measurements of ΔH should provide a good basis for assessing ΔT_o for a wide range of alloys and irradiation conditions.

PROGRESS AND STATUS

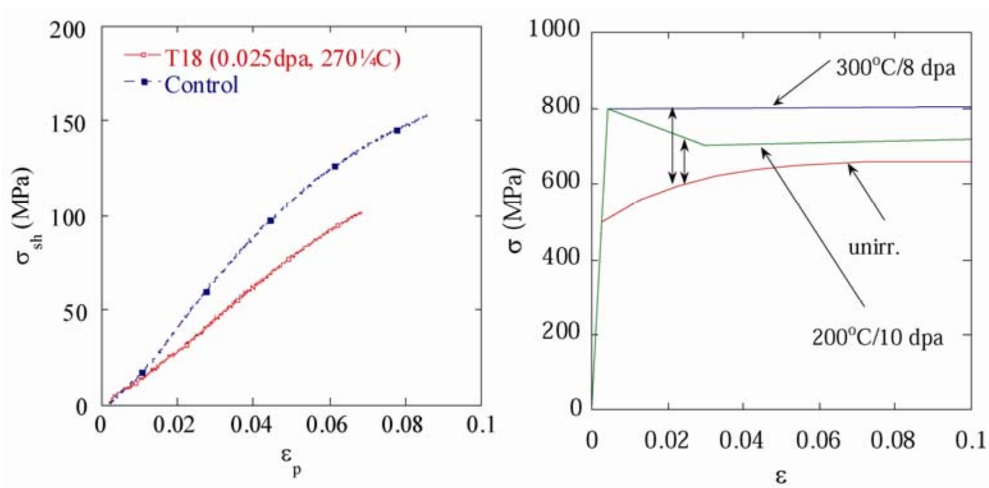
Introduction

The master curve (MC) method is based on the empirical observation that in the cleavage transition fracture toughness temperature curves [$K_{Jc}(T)$], for a wide variety of ferritic alloys and alloy conditions, have an approximately constant shape [1-4]. The master curve shape can be indexed on a relative temperature scale [$(T - T_o)$] by a reference temperature (T_o) at 100 MPa√m. It is believed that the $K_{Jc}(T-T_o)$ curve is invariant for a wide range of T_o, including following irradiation, leading to T_o shifts (ΔT_o). It is also well established that shifts in both Charpy indexed (ΔT_c) and fracture toughness (ΔT_o) cleavage transition temperatures induced by neutron irradiation below about 400°C are primarily due to hardening [1-3, 5-7]. Thus, it is common to correlate ΔT_c and ΔT_o with irradiation induced increases in the yield stress ($\Delta\sigma_y$). Analysis of data for low dose (typically < 0.06 dpa) ≈ 300°C irradiations of Mn-Mo-Ni low alloy reactor pressure vessel steels, shows that $C_o = \Delta T_o/\Delta\sigma_y \approx 0.7\pm0.2$°C [2]. The corresponding values for higher dose (>1dpa) ≈ 300°C irradiations of 9Cr tempered martensitic steels (TMS) are generally smaller with C_o < ≈ 0.6 °C, and even much less in some cases, particularly for lower irradiation temperatures (T_i) [1,7,12]. Thus, it is important to understand and model the mechanisms responsible for differences in C_o. In this paper, we focus on in the hardening dominated embrittlement regime, within the framework of a critical micro-cleavage stress (σ^*)-critical stressed volume (V^*) model of $K_{Jc}(T)$ [1,3,8-11,13,14]. However, in this case we use a two-dimensional small scale yielding model, with T-stresses equal to 0, where the local fracture properties are expressed in terms of a critical area (A^*) within a specified $\sigma_{22} = \sigma^*$ stress contour. Here, σ_{22} is the stress normal to the crack plane. For finite dimensions $V^* = BA^*$, where B is the crack front length, assuming full constraint.

Effects of Irradiation on $\sigma_{fl}(\varepsilon)$

Within the framework of the hardening dominated shift model, the $\Delta\sigma_{fl}(\varepsilon)$ is the strength property controlling ΔT_o. Thus, it is critical to properly treat the combined effects of irradiation, alloy type, test temperature and strain rate over a proper ε range. Unfortunately, information needed to build appropriate $\sigma_{fl}(\varepsilon)$ models is limited, especially for irradiated alloys with high σ_y and low σ_{sh}, leading to very low to negligible uniform strains, almost immediate necking upon yielding and, in many cases, internal flow localization. Conditions associated with post yield strain softening offer even greater complications. Thus, we will consider general trends between the unirradiated alloys and the corresponding irradiation conditions.

Figure 1a shows an example of the effect of low dose 0.025 dpa, 270°C irradiation on the room temperature $\sigma_{sh}(\varepsilon)$ for high sensitivity (0.2% Cu and 1.6% Ni) RPV steel. Note, we show $\sigma_{sh}(\varepsilon)$ rather than $\sigma_{fl}(\varepsilon)$ to make the effects of irradiation on strain hardening more visible. In this extreme case producing a large $\Delta\sigma_y \approx 400$ MPa, $\Delta\sigma_{sh}(\varepsilon)$ is modest; for example, at $\varepsilon = 0.025$, $\Delta\sigma_{sh}(0.025) \approx -20$ MPa. For a lower $\Delta\sigma_y \approx 200$ MPa case (CM19-T16 not shown) the $\Delta\sigma_{sh}(0.025) \approx -10$MPa. For RPV steels and irradiation conditions the general trend is $\Delta\sigma_{sh}(0.025) \approx -0.05\Delta\sigma_y$. Thus, irradiation induced $\Delta\sigma_{sh}$ is expected to have little effect on the $C_o = \Delta T_o/\Delta\sigma_y$ relation for RPV steels. Figure 1b shows the corresponding $\sigma_{fl}(\varepsilon)$ for the TMS F82H. Note the strain hardening in the *unirradiated* TMS alloy is more rapid compared to the RPV steels. For example, at $\varepsilon = 0.025$ the unirradiated σ_{sh} are ≈ 115 MPa and 50 MPa in the unirradiated TMS and RPV alloys, respectively. This difference is the consequence of the finer scale tempered martensite lath packet microstructure in TMS, compared to the bainitic microstructure RPV steels [16, 19-21].



a b

Fig. 1. a) an example of the effect of low dose 0.025 dpa, 270°C irradiation on the room temperature $\sigma_{sh}(\varepsilon)$ for high sensitivity (0.2% Cu and 1.6% Ni) RPV steel and b) $\sigma_{fl}(\varepsilon)$ curves for the F82H TMS unirradiated and irradiated to 10 dpa at 200ºC and 8 dpa at 300 ºC.

However, an even more significant effect is the much larger $\Delta\sigma_{sh}$ following irradiation in the TMS case, leading to approximately perfectly plastic or even softening behavior at high $\Delta\sigma_y$. This is also illustrated in Figure 1b showing two examples of true stress-strain $\sigma_{fl}(\varepsilon)$ curves that were derived using an finite element (FE) procedure, described elsewhere [16]. The procedure is based on simulating engineering stress-strain curves, accounting for geometry and stress state changes that occur during necking, to find a self-consistent $\sigma_{fl}(\varepsilon)$. The $\Delta\sigma_y \approx 300$ MPa for test temperatures (T_t) at T_i in both cases. The curve for a 300°C, 8 dpa irradiation is almost perfectly plastic, while that for a 200°C, 10 dpa irradiation shows softening at (≈ -100 MPa at $\varepsilon = 0.025$). Note, the assessment of strain hardening effects is further complicated by the fact that both $\Delta\sigma_y$

(lower) and $\Delta\sigma_{sh}$ (lower or higher) vary with lower $T_t < T_i$, as well as T_i. Nevertheless, as shown by the double arrow lines near $\varepsilon = 0.025$, the $\Delta\sigma_{fl}/\Delta\sigma_y$ are much smaller than for TMS alloy and irradiation conditions compared to the RPV steel case. For example, assuming perfectly plastic behavior after irradiation resulting in $\Delta\sigma_y = 300$ MPa, the TMS $\Delta\sigma_{sh}(0.025) \approx -115$ MPa compared to an estimated ≈ -15 MPa for RPV steels and irradiation conditions. Again assuming $\sigma_{fl}(0.025)$ is the controlling strength parameter, the difference in $\Delta\sigma_{sh}(0.025)$ would result reduction in the nominal $C_o = \Delta T_o/\Delta\sigma_y$ from ≈ 0.7 to ≈ 0.46°C/MPa. Assuming softening of 100 MPa following irradiation, would further reduce C_o to ≈ 0.3°C/MPa.

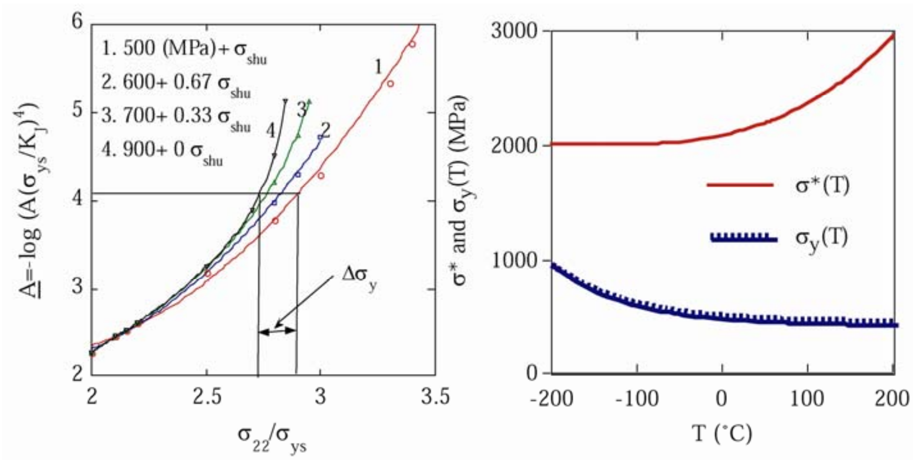


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Fig. 2. a) $\log A_o$ versus (σ_{22}/σ_y) derived from the FE calculations along with the corresponding polynomial fit lines and b) $\sigma^*(T)$ fitted for the $\sigma_y(T)$ derived from the least square fit to RPV and TMS database and $A^* = 5 \times 10^{-9}$ m^2.

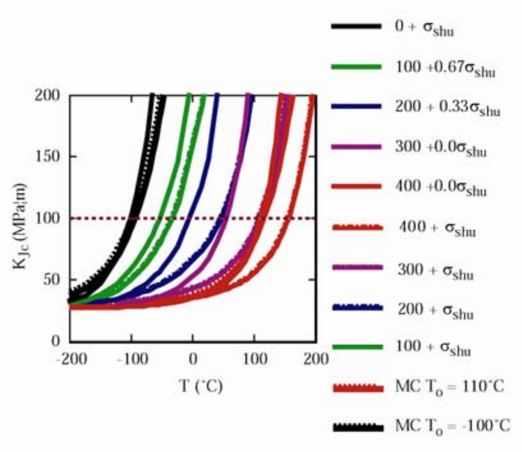
Results and Analysis

We have proposed a simple model for small scale yielding that cleavage, by either a single or few propagating micro-cracks, or quasi-cleavage involving extensive micro-cracking prior to cleavage, occurs when a $\sigma_{22} = \sigma^*$ encompass a critical *area* (A^*) [1, 7-11,13,14]. We further quantify these results based on an σ^*-A^* cleavage model, using prototypical $\sigma_{fl}(\varepsilon)$ that reflect the combined effects of irradiation on both $\Delta\sigma_y$ and $\Delta\sigma_{sh}$, as:

$$\sigma_{fl}(\varepsilon) = \sigma_{yu} + \Delta\sigma_y + \sigma_{shu}(\varepsilon) + \Delta\sigma_{sh}(\varepsilon) \quad (1)$$

Here the subscript u designates the unirradiated condition and the $\Delta\sigma_y$ and $\Delta\sigma_{sh}(\varepsilon)$ represent the effects of irradiation on $\sigma_y(> 0)$ and $\sigma_{sh}(< 0)$, respectively. Various $\sigma_{fl}(\varepsilon)$ were used, based on guidance form assessing trends in a large database. We specifically assume the nominal $\sigma_{shu}(\varepsilon)$ decreases by a factor of 1/3 for $\Delta\sigma_y = 100$ MPa, 2/3 for $\Delta\sigma_y = 200$ MPa and vanishes for $\Delta\sigma_y \geq 300$ MPa.

Figure 3 shows the $K_{Jc}(T)$ curves for $\Delta\sigma_y$ from 0 to 400 MPa both with (solid lines) and without (dashed lines) corresponding reductions in $\Delta\sigma_{sh}(\varepsilon)$. The predicted $K_{Jc}(T)$ curves (solid line) are reasonably consistent with the shape MC (dotted lines). Figure 4a shows the corresponding ΔT_o plotted against the $\Delta\sigma_y$. The C_o found by least square fits are 0.51°C/MPa for the reduced σ_{sh} case versus 0.66°C/MPa for the assumption that σ_{sh} is not decreased by irradiation. The nominal relation for RPV steels is also shown for comparison. Figure 4 a also shows the effect of perfectly plastic strain softening of 100 MPa, resulting in a $C_o \approx 0.36$°C/MPa for $\Delta\sigma_y = 300$ and 400 MPa resulting in corresponding $\Delta\sigma_{fl} = 200$ and 300 MPa, respectively.



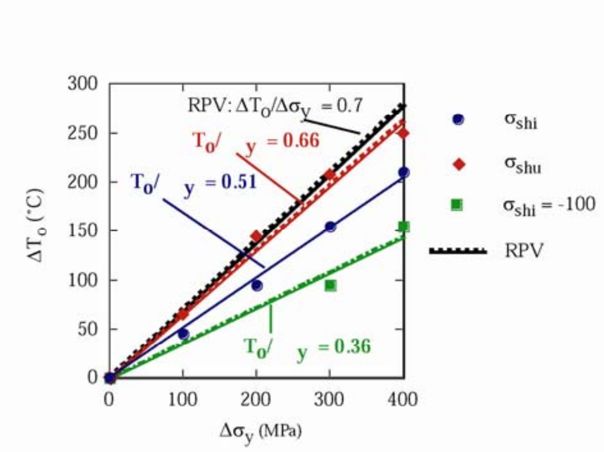
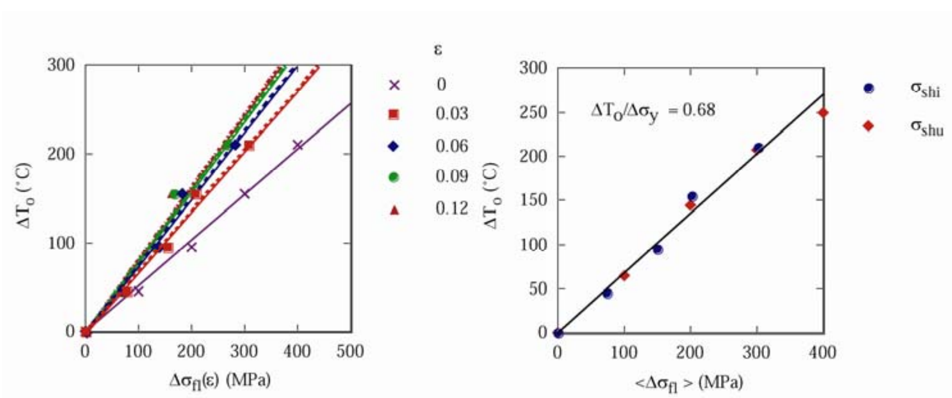


Fig. 3. $K_{Jc}(T)$ curves for $\Delta\sigma_y$ from 0 to 400 MPa both with (solid lines) and without (dashed lines) corresponding reductions in $\Delta\sigma_{sh}(\varepsilon)$.

Fig. 4. a) The corresponding ΔT_o plotted against the $\Delta\sigma_y$ for various strain hardening cases.

Clearly, irradiation induced decreases in σ_{sh} result in significant reductions in the $C_o = \Delta T_o/\Delta\sigma_y$ relation. Put simply, part of the $\Delta\sigma_y(> 0)$ is wasted (or recovered) by simultaneous $\Delta\sigma_{sh}(< 0)$. In principle, this effect could be accounted for by defining ΔT_o in terms of a $\Delta\sigma_{fl}$ at a specified ε, $C_{o'} = \Delta T_o/\Delta\sigma_{fl}(\varepsilon)$, or averaged over a pertinent range of ε, $<\Delta\sigma_{fl}>$, $C_{o'} = \Delta T_o/<\Delta\sigma_{fl}>$. Figure 4b shows $\Delta T_{0'}$ as a function of the $\Delta\sigma_{fl}(\varepsilon)$ for various ε as indicated in the legend. The calculated points approximately fall along the same line with different $C_{o'}$ slopes. The $C_{o'}$ = 0.69°C/MPa at ε = 0.03, which close to the C_o for the case where $\Delta\sigma_{fl} = \Delta\sigma_y$, with no reduction in strain hardening. However, it is not clear that a single specified strain is applicable in all cases, and the $C_{o'} = \Delta T_o/<\Delta\sigma_{fl}>$ based on averaging $\Delta\sigma_{fl}$ may be more general.

We have shown elsewhere that there is a universal relationship between indentation hardness (H) and the average σ_{fl} between ε = 0 to 0.1, $<\sigma_{fl}>_H$ [24,25]. Figure 4c plots ΔT_o versus $<\Delta\sigma_{fl}>_H$ for both cases with and without reduction in σ_{sh}. The ΔT_o all approximately fall along a single line with $C_{o'} = \Delta T_o/<\Delta\sigma_{fl}>_H$ = 0.68°C/MPa. This suggests that there may be a universal relation between ΔT_o and ΔH (or its $<\Delta\sigma_{fl}>_H$ equivalent).



b c

Fig. 4. b) $\Delta T_{0'}$ as a function of the $\Delta\sigma_{fl}(\varepsilon)$ for various ε and c) ΔT_o versus $<\Delta\sigma_{fl}>_H$ for both cases with and without reduction in σ_{sh}.

Concluding Remarks

In this work we addressed two key questions. First, how does $\Delta\sigma_{sh}$ influence the $C_o = \Delta T_o/\Delta\sigma_y$ relation? Second, is it possible to derive a universal relation between ΔT_o and $\Delta\sigma_{fl}$ averaged over a pertinent range of ε, $<\Delta\sigma_{fl}>$, such that a $C_{o'} = \Delta T_o/<\Delta\sigma_{fl}>$ is independent of the individual values of $\Delta\sigma_y$ and $\Delta\sigma_{sh}$. The results suggest that $<\Delta\sigma_{fl}>$ averaged between $\varepsilon = 0$ to 0.1 provides a similar $C_{o'}$ for various assumptions about the effect of irradiation on $\Delta\sigma_{sh}$. Notably, changes in indentation hardness, ΔH, are also directly related to this same $<\Delta\sigma_{fl}>$. Hence, measurements of ΔH should provide a good basis for assessing ΔT_o for a wide range of alloys and irradiation conditions.

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