A UNIFIED MODEL FOR CLEAVAGE TOUGHNESS IN THE TRANSITION – G. R. Odette (University of California Santa Barbara)

OBJECTIVE

The objective of this research is to develop advanced methods for defect tolerant integrity assessments that will enable the use of small specimens in generating an irradiated fracture toughness data base and for fusion applications atypical of traditional heavy section structures based on fundamental understanding of fracture micro-mechanisms, mechanics and irradiation embrittlement.

SUMMARY

A Master Curves-Shifts (MC-ΔT) method has been previously proposed as an engineering expedient to enable the use of small specimens to predict the effects of geometry, irradiation, loading rates on fracture conditions for large fusion structures. However, in addition to other unresolved issues, the MC-ΔT requires a better basic understanding, including the universality of the MC shape. Thus a new unified micromechanics model of fracture toughness in the cleavage transition regime is proposed. The model combines analytical representations of finite element method simulations of crack tip stress fields with a local critical stress-critical stressed area (σ^*-A^*) fracture criteria. The model, and simpler alternatives, have been very successful in predicting geometry and loading rate effects, as well as irradiation hardening induced Charpy shifts. However, the standard models do not predict a constant MC $K_{Jc}(T)$ shape following irradiation. This apparent inconsistency with experiment is now resolved by incorporating a modest temperature dependence in σ^* that appears to be consistent with an independent body of data. Several experiments suggest high helium levels may increase irradiation induced toughness temperature shifts above levels associated with hardening alone. However, these experiments are all confounded, and must be interpreted with great caution. If real, helium effects may be relatively modest. Single variable experiments and complementary data which will allow a mechanism-based interpretation of the mechanical test data are needed to characterize the influence of helium on fast fracture.

PROGRESS AND STATUS

Backround

A master curves (MC)-shifts (ΔT) method has been previously proposed as a possible practical approach to dealing with the enormous amount of information that is needed to characterize and apply fracture toughness [1]. Following the approach for heavy section applications [2], the MC-ΔT method assumes a master toughness $K_{Jc}(T')$ curve shape can be placed (indexed) on an absolute temperature (T) scale by a reference temperature ($T' = T - T_{or}$) at a reference toughness (e.g., 100 MPa√m). An illustration of the MC-ΔT method is shown in Figure 1. The static MC deep crack shape is shown as the dashed line plotted on a $T - T_{or}$ scale. The solid line is the corresponding reference (unirradiated) MC placed on an absolute temperature scale, at T_{or} = -50°C, by six tests shown as filled circles. A net shift of 200°C, arising from irradiation (ΔT_{oi} = 150°C), dynamic loading ($\Delta T_{P'}$ = 50°C), a thin-walled, shallow crack geometry (ΔT_g = -40) and a margin (ΔT_m = 40°C), places the absolute MC, used for in-service structural evaluations, at T_o = 150°C, shown as the dotted line. Ideally, there would be only a single MC shape applicable to all conditions. While, in practice this is not the case, a small family of MC shapes may be sufficient for most practical purposes. The key advantage is the $K_{Jc}(T)$ curves can be established with a relatively small number of tests on small relatively small specimens; and b) effects of other key variables would be accounted for by direct measurement or independently established shifts and a small set of MC shapes.

Open questions about MC–ΔT method include: a) Is there a constant of the MC shape, or small set of shapes, and if so why? b) How should effects of size and geometry, in both testing and applications, be treated? c) How can T_{or} and the ΔTs be modeled to characterize effects of irradiation; d) What are the effects of high helium?

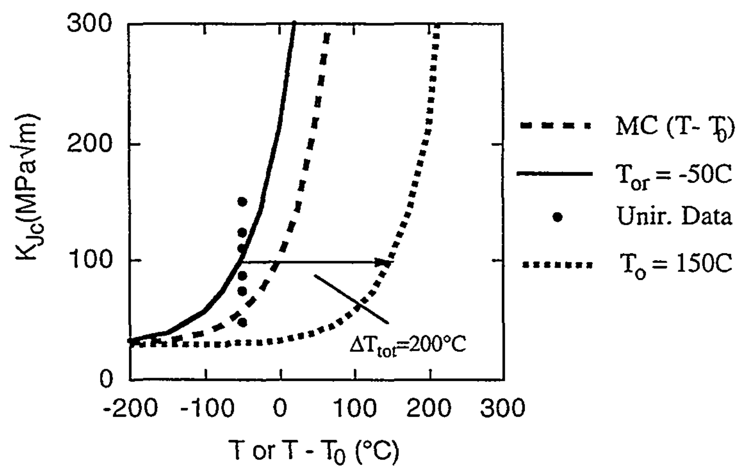

Figure 1. Illustration of the MC-ΔT method.

Macro-Micromechanics of the MC and Cleavage Intitiation Toughness in the Transition – A Unified Model.

It is generally accepted that cleavage fracture involves stress controlled fracture of brittle 'trigger' particles (e.g., grain boundary carbides) and subsequent dynamic micro-cleavage crack propagation into the tougher metal matrix []. Models of cleavage toughness require combining simulations of the crack tip stress fields with local micromechanical models of the field conditions required to initiate cleavage. A useful local fracture criteria is a critical stress (σ*) acting over a critical area in front of the blunting crack (A*). Based primarily on blunt notch tests, and the coarse (μm) scale of the microstructures involved, a typical assumption has been that σ*-A* are independent of temperature, strain rate and, in many cases, irradiation exposure [1,3-7].

For deep cracks in sufficiently large cracked bodies or small scale yielding (SSY) conditions K_{Jc} can be analytically represented in terms of A* and R =σ^*/σ_y, where σ_y is the yield stress as [8,9]

$$K_{Jc} = \sigma_y[A^* 10^{P^*}]^{1/4} \quad (1)$$

where $P = C_o + C_1R + C_2R^2$; and the C_i are determined from fits to the FEM results for a given constitutive law.

For cases with shallow cracks or large scale plastic deformation outside the SSY regime, the effective toughness (K_e) is larger than K_{Jc} due to the loss of constraint [8,9]. The K_e/K_{Jc} ratio is a function of R, the constitutive law, the cracked body geometry and the deformation level D = $K_e^2/bE\sigma_y$, where the characteristic dimension is usually taken as the uncracked ligament length, b. For a specified geometry and constitutive law, K_e/K_{Jc} can be analytically fit to results of FEM simulations with simple polynomial expressions in the form [].

$$K_e/K_{Jc} = [C_{co} + C_{c1}R^* + C_{c2}R^{*2}]^{1/2} \quad (2a)$$

where the C_{ci} coefficients depend on D as

$$C_{ci} = C_{rio} + C_{ri1}D + C_{ri2}D^2 \quad (2b)$$

Equations 1 and 2 represent a unified model of effective fracture toughness in the transition region.

Application of the model is illustrated in Figure 2, where the predicted $K_{Jc}(T)$ shape (solid line) is compared to the MC for pressure vessel steels with T_{or} = - 50°C (dashed line). The model parameters are $A^* = 10^{-8}$ m², σ^* = 2080 MPa and a power law strain hardening exponent of n = 0.1 and $\sigma_y(T)$ fit to RPV steel data. The dotted line shows the corresponding $K_e(T)$ curve for a small 3.3x3.3x16.6 mm (1/3 sized Charpy) specimen tested well beyond the SSY limit.

The broad success of the simple constant σ^*/A^* model have been discussed previously []. However, one key limitation of this model is that significant reductions in the slope of the $K_{Jc}(T)$ curves in the transition are predicted at high T_o, associated with severe irradiation hardening. Such shape changes have generally not been observed. This is illustrated by the dashed line in Figure 3 for $\Delta\sigma_y$ = 200 MPa. Thus we must seek a fundamental explanation for the constant MC shape. The standard assumption is that σ^*-A* are independent of temperature. However, we challenge assumption by using Equation 1 to estimate the $\sigma^*(T)$ that is consistent with experimental observations for RPV steels: a) a MC-type shape over a wide range of T_o; and b) the observed ΔT as a function of $\Delta\sigma_y$.

The results of this exercise are shown as the heavy solid lines in Figure 4 for $A^* = 10^{-8}$ m² and $\Delta\sigma_y$ of 0, 100, 200 and 300 MPa. The thinner, dashed lines are RPV steel MCs indexed at the same 100 MPa√m-temperature as the model predictions. Figure 5 compares the corresponding predicted temperature-shifts at 100 MPa√m as a function of $\Delta\sigma_y$ (solid line) with experimental data (filled circles) compiled by Sokalov [10] and the least squares fit to this data (dashed line). As discussed in more detail elsewhere, as well as a body of independent data and theoretical considerations are qualitatively the empirical $\sigma^*(T)$ derived in this work [11].

Implications to Irradiation Embrittlement

Figure 6 shows MC fits to for F82H data before and following irradiation to 2.5 dpa at 300°C [12]. Charpy and fracture toughness temperature shifts have also been treated previously using a simple equivalent yield stress model (EYSM) [1,13]. An example of the model predictions for several F82H Charpy and a single ΔT are shown in Figure 7. There results confirm that irradiation hardening results in toughness shifts in both RPV and martensitic steels, with a typical ration of $\Delta T/\Delta\sigma_y$ of about 0.7±0.2 °C/MPa.

The potential effect of transmutation helium on fast fracture is a complex and contentious issue, that cannot be effectively resolved at this time since all existing experiments that have been interpreted to show a effect of helium may be confounded by uncontrolled or unaccounted for variables. However, several available data sets do seem to consistently show that higher helium levels increase $\Delta T_{\phi t}$ [14-20]. For irradiation at around 300°C, the maximum $\Delta T_{\phi t}$ attributable to helium differences appears to be about 70°C for 300 appm helium. The corresponding normalized $\Delta T_{\phi t}$/He mean and median values for these studies are about 0.15 and 0.11 °C/appm. However, even if these crude estimates are accurate, there is no logical basis or physical justification to linearly extrapolate possible enhanced shifts to very high helium levels. Indeed, at worst, effect of helium on shifts should be of order, or less than, that produced by displacement damage. There is some indication that helium effects may be more significant at higher irradiation temperatures, but this may be mitigated by reduction is the corresponding contributions due to irradiation hardening.

The models described in this work provide a useful framework for considering the existing data, and designing new experimental approaches to evaluate helium effects on fracture. For example, it is clear that to the extent that higher levels of helium lead to larger $\Delta\sigma_y$, corresponding increases in $\Delta T_{\phi t}$ are anticipated. In general, however, the limited database indicates that increases in $\Delta\sigma_y$ at higher helium levels are modest. Thus the implication is that helium effectively reduces σ^*. Shifts that increase with helium, and that are much larger than can be attributed to $\Delta\sigma_y$ alone, would support this hypothesis. However, such data is lacking. Helium effects on fast fracture, if any, must be better characterized by well-designed experiments. Ideally, single variable experiments would involve only controlled differences in helium levels, with all other variables held constant. In practice, this is very hard to achieve; thus the effects of potentially confounding factors must always be carefully considered. Nickel and iron isotope tailoring experiments probably come the closest to achieving this ideal, but to date have provided limited opportunity for fracture testing. However, an equally important objective of such experiments should be to obtain the body of the complementary data (constitutive properties, fractography, microstructure,...) so that the test results can be interpreted and linked to the models, such as those described in this report.

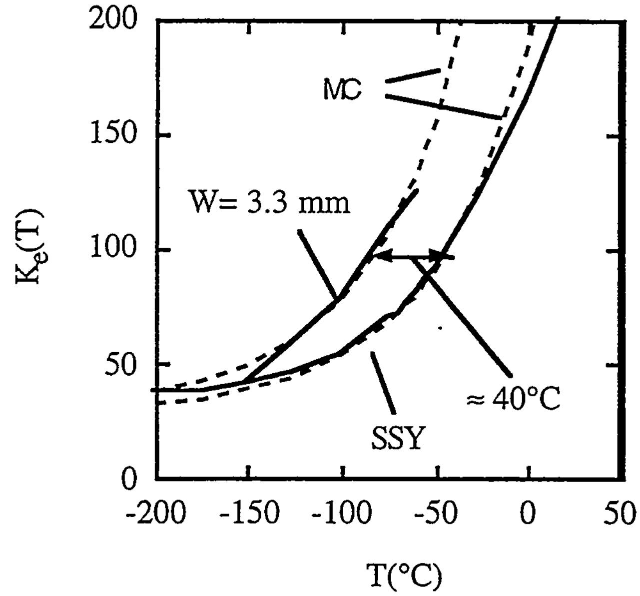

Figure 2. $K_{Jc/e}(T)$ curves from Equations 1 and 2 for SSY and a subsized specimen.

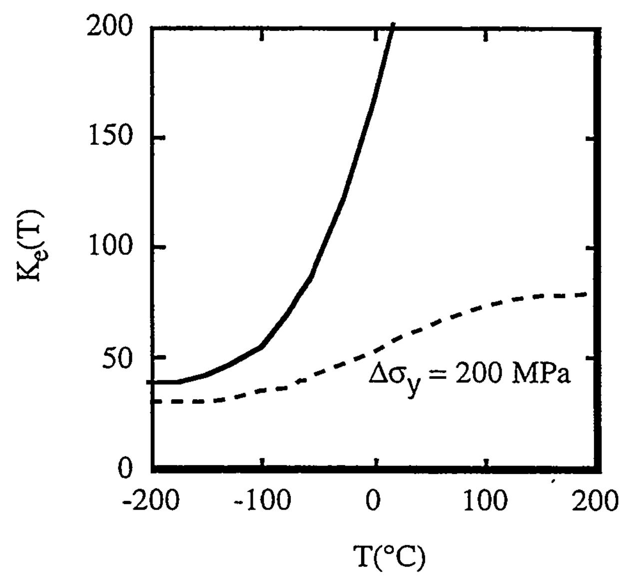

Figure 3. The corresponding predicted $K_{Jc}(T)$ for $\Delta\sigma_y$ = 200 MPa.

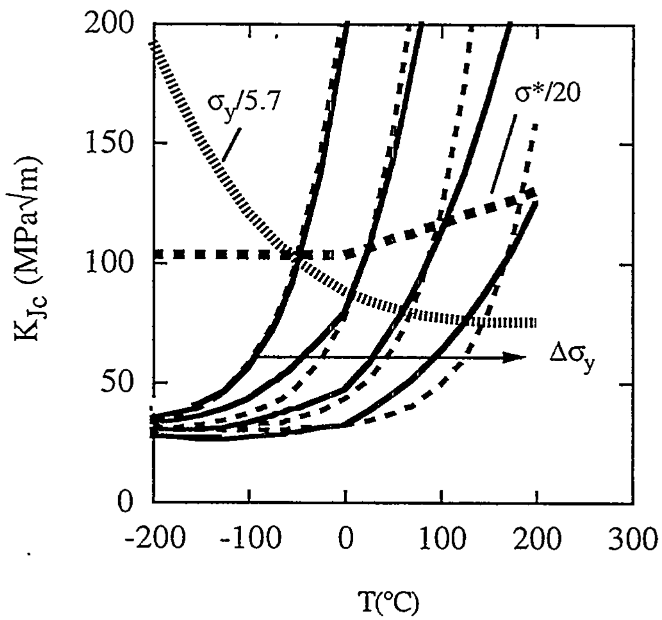

Figure 4. Predicted vs. MC shapes for fitted σ*(T)/A*.

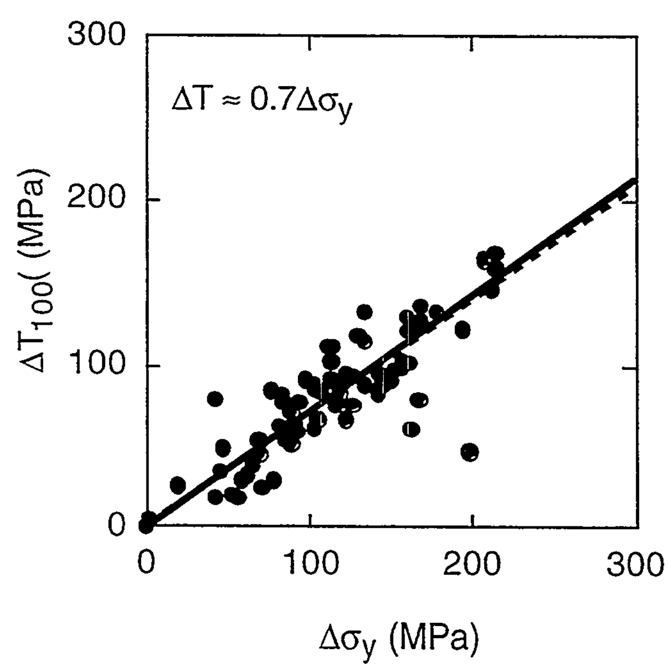

Figure 5. Predicted and measured ΔT_{K100} versus $\Delta\sigma_y$ for RPV steels.

Summary and Conclusions

A Master Curves-Shifts (MC-ΔT) method has been proposed as an engineering expedient to enable the use of small specimens consistent with predicting the effects of geometry, irradiation and loading rates on the fracture of fusion structures. In support of the MC-ΔT method a new unified model of fracture toughness in the cleavage transition regime is proposed which is consistent with a constant $K_{Jc}(T)$ MC shape and ΔT versus $\Delta\sigma_y$ data for both RPV and martensitic steels. While there are no unambiguous results regarding the potential role of helium on fast fracture, several experimental data sets do suggest that high helium levels increase $\Delta T_{\phi t}$ above levels associated with irradiation hardening alone. However, if real, helium effects on fast fracture may be modest. Resolution of the *'helium question'* will require carefully designed single variable experiments and assembling the range of complementary data (tensile, fractrographic, microstructal) needed for mechanism based interpretations of the mechanical test data.

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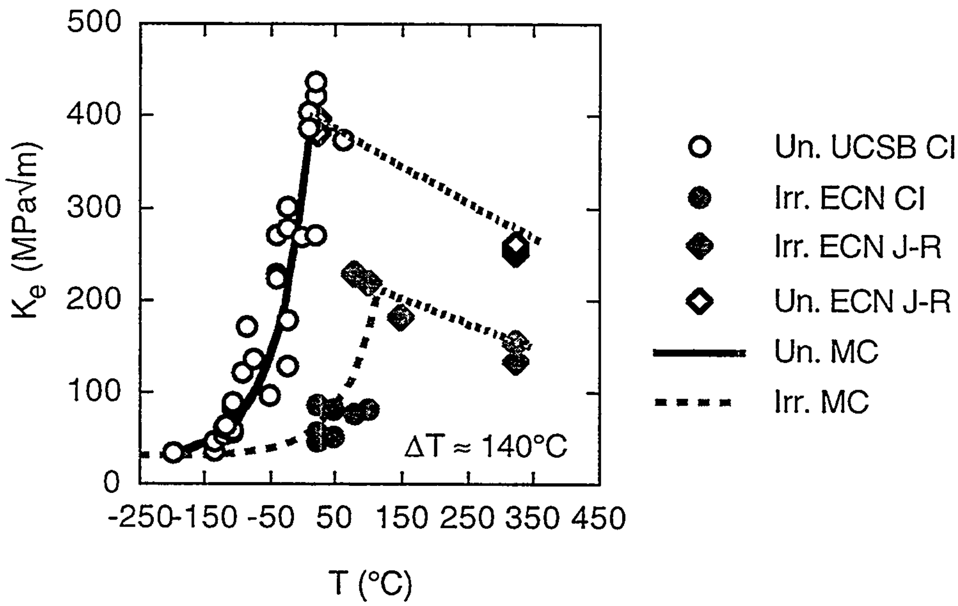

Figure 6. MC fits to F82H data before and after irradiation to 2.5 dpa at 300°C.

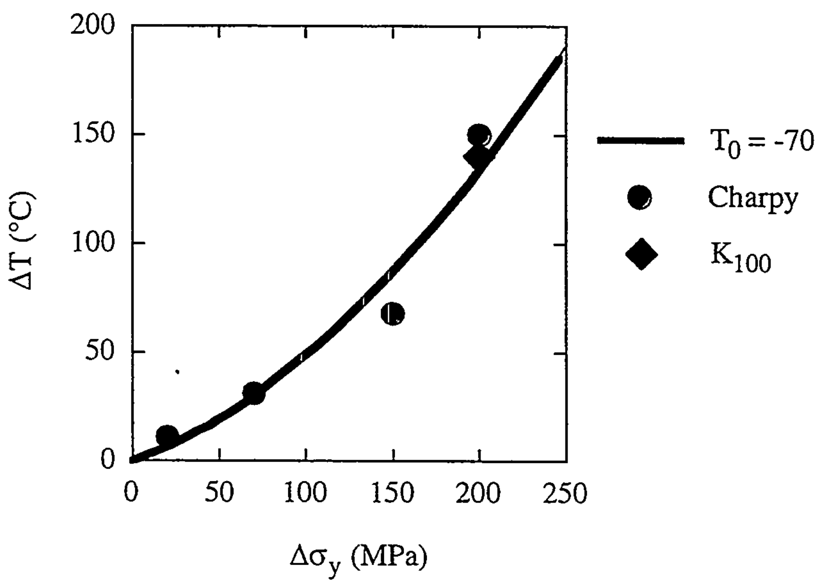

Figure 7. Predicted versus measured F82H Charpy and the toughness shifts from due to $\Delta\sigma_y$ based on the EYSM.

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