ON THE MECHANISMS AND MECHANICS OF FRACTURE IN A V-4CR-4TI ALLOY: MODELING THE EFFECTS OF IRRADIATION, LOADING RATE AND SPECIMEN CONGFIGURATION ON TOUGHNESS-TEMPERATURE CURVES –

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OBJECTIVE

The objective of this work is to understand and model the mechanics of fracture as a basis for developing fracture assessment methods for defect tolerant design of vanadium-based fusion reactor structures.

SUMMARY

The fracture behavior of the 500 kg heat of the V-4Cr-4Ti was used to characterize and model of low dose, low-to-intermediate temperature irradiation, loading rate and specimen configuration on toughness-temperature curves. A critical stress–critical stressed area cleavage criteria predicts effective toughness-temperature curves in the cleavage transition regime, including the influence of size and geometry that mediate the loss of triaxial constraint. It appears that cross rolling lowers the cleavage transition temperature. Irradiation and high loading rates result in significant upward shifts in the transition temperature, due to corresponding increases in the yield stress. A simple equivalent yield stress model accurately predicts these effects. Flow localization following irradiation has a profound effect on effective ductile fracture toughness, qualitatively consistent with effects of irradiation on the tensile properties, dominated by reductions in uniform strain. The large cleavage transition temperature shifts and ductile toughness decreases may limit the application of V-4Cr-4Ti alloys for low-to-intermediate temperature irradiation environments.

PROGRESS AND STATUS

Introduction

The objective of this work is to develop physical models for the fracture toughness of a V-4Cr-4Ti alloy that quantitatively treat the effects of: a) specimen/structure size and geometry; b) loading rate; c) metallurgical factors associated with processing and fabrication history; and d) in-service degradation processes such as irradiation embrittlement. Fracture specimens of varying size, geometry, orientation, processing history and irradiation conditions were tested. This study used small to very small specimens, with limited redundancy

Experimental and Data Analysis Procedures

Details of the material fabrication and processing, specimen preparation, and fracture testing conditions are described elsewhere [1]. The effective toughness data were evaluated with both 'standard' elastic-plastic fracture mechanics methods (K_e) [2,3] and by the confocal microscopy-fracture reconstruction (CM-FR) technique (K_δ) [4,5]. Both CM-FR and scanning electron microscopy (SEM) were also used to characterize the local fracture processes and mechanisms.

In selected cases, the K_e data were constraint corrected to provide estimates of K_{Jc} based on a critical stress (σ^*)/critical area (A^*) local fracture model coupled with three dimensional finite element method (FEM) calculations of crack tip stress and strain fields. Details of this model are described elsewhere [6-8]. The σ^*–A^* model can be used to compute mean $K_e(T)$ curves for a given specimen and constitutive law [6]. In the limiting case of SSY the $K_{Jc}(T)$ curve is unique. The

K_e data outside the SSY regime, can be corrected to K_{Jc} based on FEM calculations of the K_e/K_{Jc}-ratio needed to produce the same stressed area.

Irradiation and loading rate induced shifts in the cleavage transition temperatures ($\Delta T_{\phi t/P'}$) were compared to predictions of the equivalent yield stress model (EYSM) [9]. A key assumption is that σ^* is independent of irradiation, loading rate and temperature.

Corresponding reductions in the maximum load toughness can be crudely predicted based on a decohesion model proposed for irradiated stainless steels [10]. In its simplest form, the ratio of the irradiated (i) to unirradiated (u) toughness can be estimated from tensile properties as given by

$$K_{maxi}/K_{maxu} \approx \{[(\sigma_{yi} + \sigma_{ui})/(\sigma_{yu} + \sigma_{uu})](\varepsilon_{ui}/\varepsilon_{uu})\}^{1/2} \qquad (1)$$

where σ_u are the ultimate tensile stresses and ε_u are the uniform strains.

Results

Figure 1 shows toughness data from MPCC tests from rolled versus crossrolled plate in the LT orientation. The crossrolled material exhibited higher toughness associated with a downward shift of $K_e(T)$ data by about 20°C. The effects of specimen orientation was investigated in two different plates. These comparisons suggest a slightly higher toughness for the TL orientation versus LT for bend bars from the thin plate. However, there was essentially no difference in toughness between the two orientations of 0.26T CT specimens taken from the thick plate.

Figure 2 shows the raw K_e data (open symbols), the constraint corrected K_{Jc} data (filled symbols) for each MPCC specimen, and the SSY $K_{Jc}(T)$ curves (lines) for both rolled and crossrolled plates. A value of $A^* = 10^{-8}$ m^2 was used for both sets of specimens. The σ^* were 1750 (rolled) and 1900 (crossrolled) MPa. The constraint corrected data lie close to the SSY line.

Since σ_y increases with increasing strain rate [11], higher loading rates shift $K_e(T)$ curves to higher temperature as reported previously [12]. The measured shifts associated with rate increases by factors of 10^5 (low-dynamic) and 10^6 (intermediate-dynamic) were about 60 and 70°C, respectively.

Irradiation at low-to-intermediate temperatures also results in significant elevations of σ_y, even at relatively low dose [13-15]. Data for smooth-sided MPCC specimens irradiated to ~ 0.4 dpa at 200°C [13] shows a shift of about 165°C with a corresponding $\Delta\sigma_y$ ~ 330 MPa [16]. As discussed in more detail elsewhere [12], CM-FR and SEM show that irradiated versus unirradiated cleavage fracture surfaces and processes are generally similar. However, there is abundant evidence of irradiation enhanced flow localization in the form of coarse slip steps; and, in some cases, even extrusions bridging transverse cracks that penetrate into the fracture surface. Large scatter in the cleavage K_e is also evident. Indeed the largest values of cleavage toughness are higher than the values of maximum load ductile toughness, K_{max}. The irradiated K_{max} toughness of about 95 MPa√m was much lower than for the unirradiated material and, in contrast to the blunting-only behavior in the latter case, involved tearing and sliding-off along slip bands of highly concentrated deformation. Figure 3 shows that irradiations to ~ 0.1 dpa at 160 and 255°C [14] produced even larger reductions in the K_{max}. CM-FR and SEM also indicated more pronounced tearing and crack sliding-off. Significant elevations of the cleavage transition temperature were also observed. However, since the maximum load and cleavage toughness are of the same order, only about 60±10 MPa√m at 160°C, it is difficult to define a cleavage transition temperature shift. The reductions in maximum load toughness are smaller for the 0.1 dpa irradiations at higher irradiation

temperatures of 390 and 295°C, and the increases in the cleavage transition temperature more obvious.

Figure 4 shows that the measured shifts in cleavage transition temperature ($\Delta T_{\phi t,P}$) due to irradiation and loading rate are in excellent agreement with predictions of the EYSM and the corresponding elevations in σ_y ($\Delta\sigma_y$). Details of the method for estimating shifts due to loading rate differences are described elsewhere [6]. Figure 4 also includes results from Alexander et. al. [13]. The apparent success of the EYSM in predicting cleavage transition temperature shifts is somewhat puzzling, in view of the severe flow localization which occurs in this alloy, particularly after irradiation. Figure 5 compares the the predictions of the ratio of the irradiated to unirradiated toughness estimated by Equation 1 using tensile data from the literature [14,15] with the experimental estimates of the K_{max}.

The dominant effect of irradiation on K_{max} is associated with reductions in the uniform strain (ε_u) from ε_{uu}~ 0.15 to ε_{ui} as low as 0.001. While Equation 1 is consistent with the observed trends, it underpredicts K_{max} at lower irradiation temperatures. Indeed, tensile tests show substantial post-uniform strains prior to fracture, as well as significant reductions in area [14]. An illustration of the effect of using higher irradiated strains in Equation 1 is shown as the filled diamond symbols in Figure 5, where ε_{ui} has been replaced by ε_{ui} + 0.01. Although somewhat arbitrary, this modest adjustment produced much better agreement with the experimental estimates. Another observation that may seem puzzling is also qualitatively consistent with this model. That is in the irradiation temperature range of 150 to 250°C, the lowest dose 0.1 dpa irradiation produce similar or even larger reductions in K_{max} than irradiations to 0.4 dpa at 200°C. This can be understood by the competing effects of ε_{ui} and σ_{yi}. Specifically, ε_{ui} decreases and the propensity for localization increases more rapidly than the corresponding increases in σ_{yi}.

Developing more rigorous fracture models will require detailed characterization of the underlying physical processes. Fractographic evidence of the flow localization and its consequences is seen in the form of coarse slip steps, transverse microcracks, flat-bottomed voids and extrusion-type features on the fracture surfaces. Further quantification of these phenomena to guide the development of new fracture models for the range of fracture modes from cleavage to decohesion will be the focus of future research.

Summary and Conclusions

A micromechanical model based on a critical stress-critical stressed area, σ^*-A^*, cleavage criteria provides a basis for predicting effective toughness-temperature, $K_e(T)$, curves in the cleavage transition regime, including the effects of size and geometry pertinent to the use of small specimen data to estimate the fracture limits of structures. The cleavage transition temperature of the as-fabricated alloy is high due to its relatively low strength (e.g., lower than typical steels) combined with a high σ^* (comparable to typical steels). It appears that crossrolling lowers the transition temperature. The effects of low strength on toughness is amplified in small specimens by the loss of triaxial constraint.

Irradiation and high loading rates result in significant upward shifts in the cleavage transition temperature. The shifts are largely due to corresponding increases in the yield stress. Notably, the σ^*-A^* concept also provides the basis for an apparently effective way to predict these effects using the simple equivalent yield stress model (EYSM). However, the reason for this success is not fully understood, in view of the severe flow localization observed in irradiated alloys.

Flow localization following irradiation has even more profound effects on effective ductile fracture toughness, K_{max}, defined in this work as the K_J at maximum load in the load-displacement curve. The trends in the experimental estimates of K_{max} are qualitatively consistent with a simple model based on effects of irradiation on the tensile properties, as dominated by reductions in uniform strain. However, more realistic models reflecting the complexities of the underlying physics are needed and are under development.

Finally, it is clear that the large cleavage transition temperature shifts and ductile toughness decreases may limit the application of V-4Cr-4Ti alloys for low-to-intermediate temperature irradiation environments.

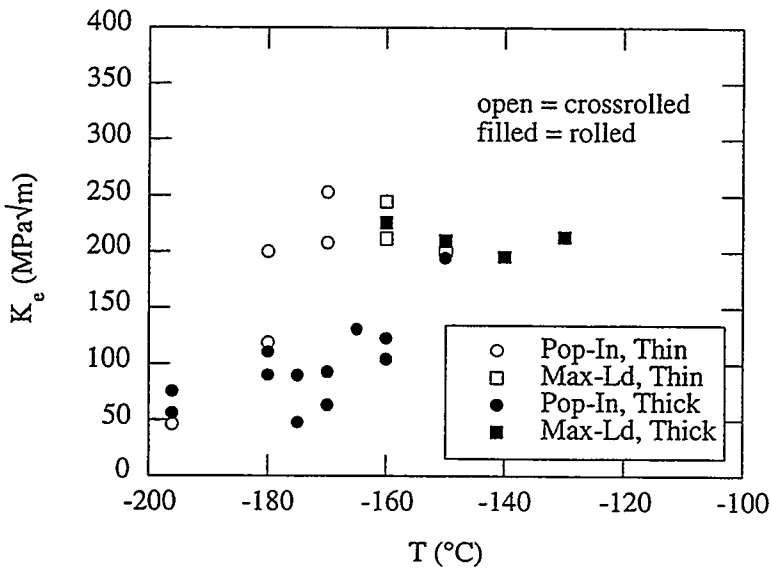

Figure 1. $K_e(T)$ data from MPCC tests from rolled and crossrolled plate. Both sets of specimens were in LT orientation with respect to the last rolling direction. The crossrolled material exhibited higher toughness associated with a downward shift in the $K_e(T)$ curve.

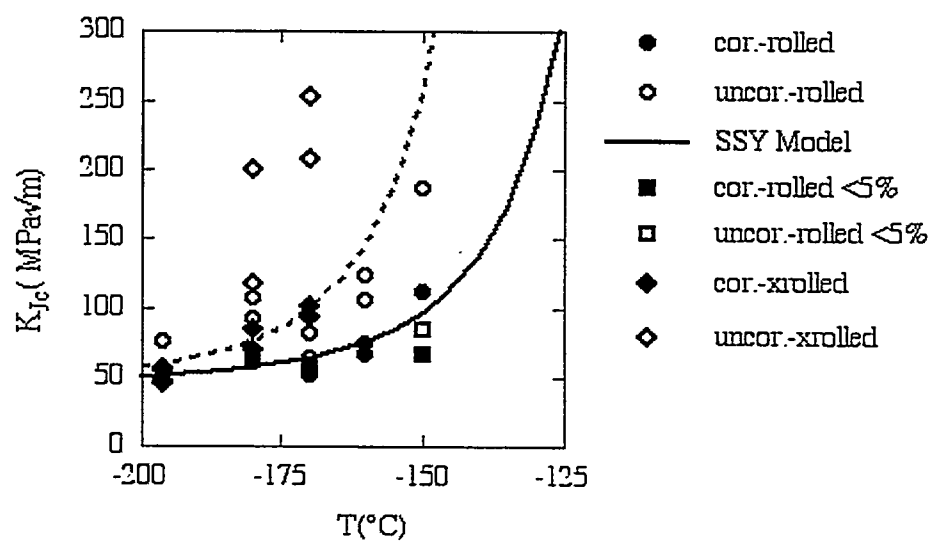

Figure 2. Constraint correction to K_{Jc} data for each MPCC specimen, and the SSY $K_{Jc}(T)$ curves for both rolling conditons, rolled and crossrolled (xrolled). The σ^*/A^* criteria used for each rolling condition differed slightly which accounts for the difference in SSY $K_{Jc}(T)$ curves.

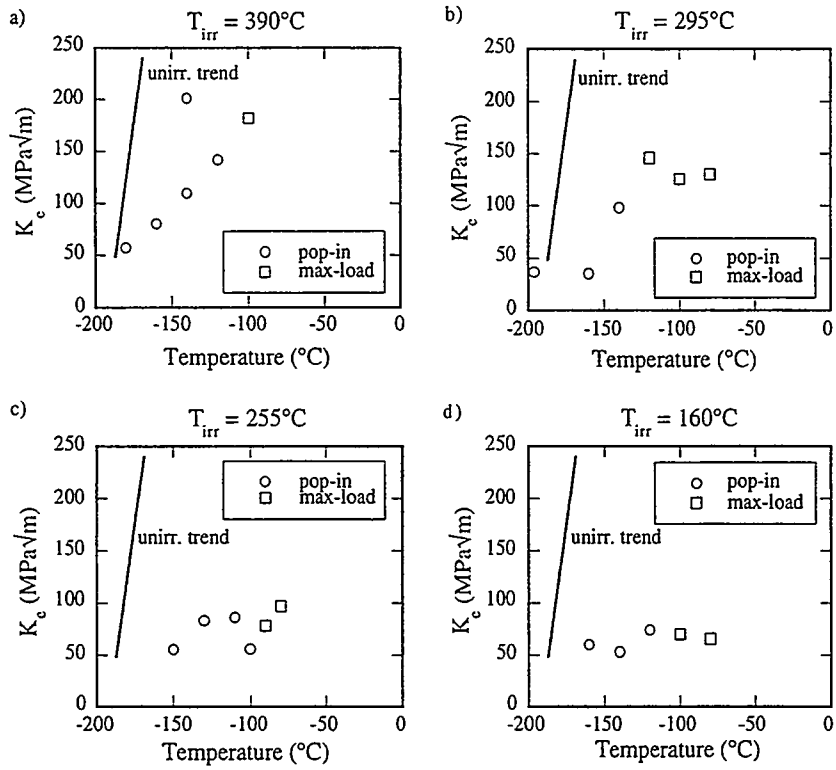

Figure 3. $K_e(T)$ data for side-grooved MPCC specimens irradiated to 0.1 dpa at (a) 390°C, (b) 295°C, (c) 255°C, and (d) 160°C.

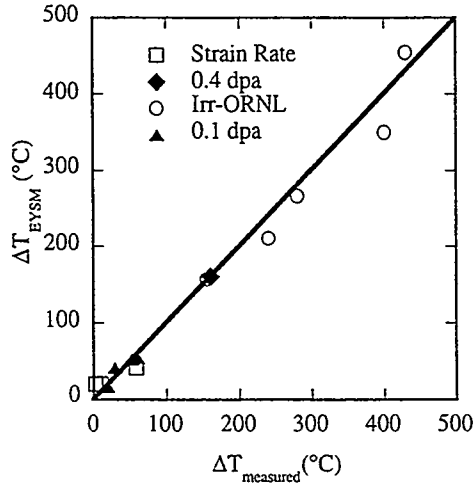

Figure 4. Comparison between measured ΔT and ΔT as predicted by the EYSM are shown showing good agreement.

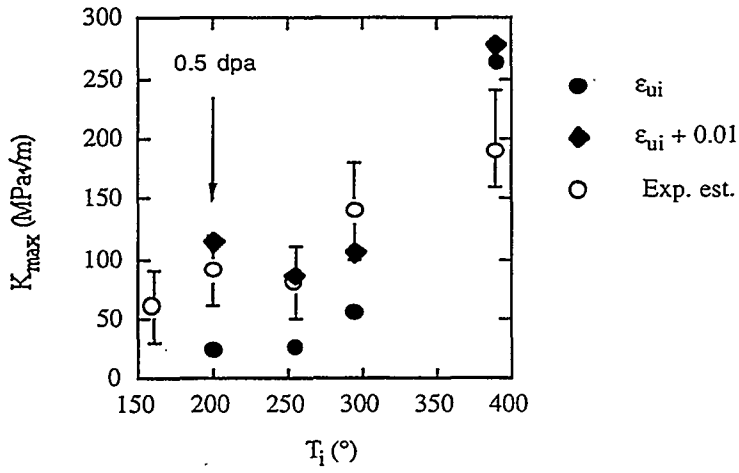

Figure 5. Comparison of the predictions of the ratio of the irradiated to unirradiated toughness estimated by Equation 1 (filled circles) using tensile data from the literature [14,15] with the experimental estimates of the K_{max} (open circles).

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