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CORRELATION OF FRACTURE TOUGHNESS WITH TENSILE PROPERTIES FOR IRRADIATED 20% COLD-WORKED 316 STAINLESS STEEL*

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A modified version of the Krafft correlation has been successfully employed to estimate the fracture toughness of irradiated AISI 316 using more easily obtained tensile data. It appears that fracture toughness saturates with neutron exposure at ∿400°C. It also exhibits a dependence on both irradiation temperature and test temperature.

1. INTRODUCTION

It has recently been shown that a reduction in fracture toughness due to irradiation can have a significant impact on the lifetime of the first wall of a fusion reactor.[1] Both the fatigue crack growth rate and the mode of failure (leak vs. sudden crack propagation) will depend on the fracture toughness.

Experimental determination of fracture toughness for irradiated materials is hampered by several considerations. First, both standard and miniature fracture toughness specimens are rather large with respect to the limited irradiation test space available in either FMIT**, fast breeder or mixed-spectrum fission reactors. Second, selection of the minimum size for valid test specimens requires some <u>a priori</u> estimate of the expected fracture toughness. For these reasons it is desirable to explore the possibility of estimating fracture toughness from the tensile properties of irradiated specimens having a much reduced size. This possibility was discussed at some length by Wolfer and Jones,[2] and it was pointed out that the appropriate correlation between fracture toughness and tensile properties is fundamentally different for materials exhibiting homogeneous plastic flow and those experiencing localized flow.

A limited number of toughness measurements have recently become available for irradiated 20% cold-worked AISI 316 stainless steel.[3-5] Tensile properties have also been determined on other segments of the component from which the toughness specimens were constructed. It is therefore possible to test relationships which attempt to correlate fracture and tensile properties.

2. THE TOUGHNESS DATA

Huang and Fish[3] performed tensile tests at 593°C on notched and unnotched specimens made from 20% cold-worked 316 ducts irradiated at 375-415°C in EBR-II to a fluence of 7.8×10^{22} n/cm^2 (E > 0.1 MeV). Based on a J-integral analysis of the load-displacement curves from two notched specimens, they obtained fracture toughness values at 593°C of 57.2 MPa $\sqrt{m}$ for irradiation at 375°C and 67.7 MPa $\sqrt{m}$ for irradiation at 415°C.

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**FMIT designates the Fusion Materials Irradiation Test Facility planned for construction on the Hanford Reservation in Richland, WA.

Huang and Wire[4] also made measurements on compact tension specimens fabricated from an EBR-II duct irradiated to fluences of 11.0 to 11.3 x 10^{22} n/cm^2 (E > 0.1 MeV) at temperatures ranging from 377 to 400°C. The test temperatures were 20, 232, 427, 538 and 649°C. These results have recently been revised slightly by Huang[5] and are shown in Figure 1. These authors[4,5] also showed that the Hahn-Rosenfield model[6] could predict the toughness for unirradiated material but not for irradiated material.

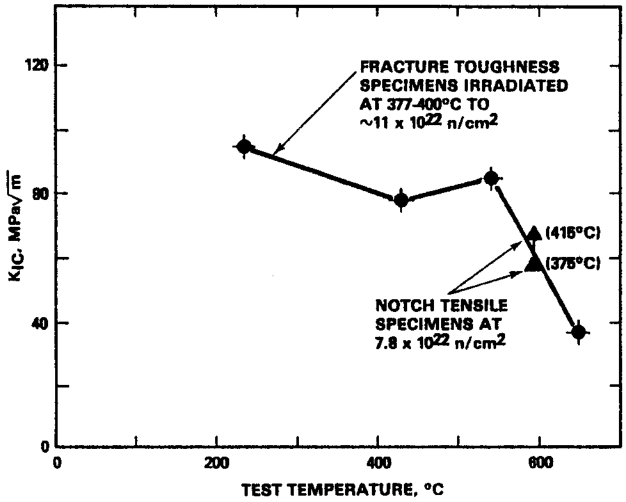

FIGURE 1
Fracture Toughness Data for 20% Cold-Worked 316 Stainless Steel, by Huang and Coworkers.[3-5] Specimens irradiated at temperatures shown.

3. THE TENSILE DATA

In addition to the data on unnotched tensile specimens reported by Huang and Fish, there exist previously unreported tensile data on unnotched specimens cut from the same EBR-II ducts from which the compact tension specimens were fabricated. As shown in Table 1 these data at 10.0 x 10^{22} n/cm^2 cover a somewhat larger range of irradiation temperature (379 and 452°C).

4. THE MODIFIED KRAFFT MODEL

The model chosen most likely to relate fracture and tensile properties is that of Krafft[7] as modified by Schwalbe and Backfisch.[8] This choice was based on the comparative success of this model over the Hahn-Rosenfield model in a similar analysis conducted on AISI 316 irradiated in HFIR[2]. The Krafft model considers fracture instability as occurring in small elemental fracture cells lying along the crack front. These cells act as coherent ductile ligaments which are the last connecting links at the crack front. Instability is visualized to occur when a critical strain develops over a specific distance ahead of the crack tip. This distance is referred to as the process zone size, which is the smallest material dimension necessary for a crack propagation element. The choice of the appropriate process zone size requires some knowledge of the nature of the fracture surface and the crack nucleation sites.

The modified Krafft correlation is given by

$$K_{Ic} = \frac{\sigma_y}{(1-2\nu)} \left\{ \pi(1+n)d^* \, (\epsilon_f \, E/ \, \sigma_y)^{1+n} \right\}^{1/2} \qquad (1)$$

where: σ_y = yield strength
ϵ_f = true fracture strain
E = Young's modulus
ν = Poisson's ratio
n = strain hardening exponent
d^* = size of the fracture process zone

The values of d^* and ϵ_f are somewhat vaguely defined, however. For irradiated austenitic stainless steels we have chosen the grain size and the total elongation, respectively. The reasons for these choices will be given in the discussion section. The average grain size of the EBR-II ducts was ~50 μm.

If power-law strain-hardening is assumed,

$$\epsilon/\epsilon_0 = (\sigma/\sigma_0)^{\frac{1}{n}} \qquad (2)$$

where ϵ_0 and σ_0 are two arbitrary reference values of the unaxial strain and stress, respectively. The strain-hardening exponent n can then be obtained from the relationship

TABLE I

TENSILE PROPERTIES AND PREDICTED VALUES OF FRACTURE TOUGHNESS FOR 20% COLD-WORKED 316 DUCTS IRRADIATED IN EBR-II TO 10 x 10^{22} n/cm^2 (E>0.1 Mev)

Irradiation Temperature = 379°C

Specimen	Strain Rate (sec^{-1})	Test Temp. (°C)	Yield Strength (MPa)	Ultimate Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)	Predicted Toughness, K_{Ic} (MPa$\sqrt{m}$)
M1D1	4.4×10^{-5}	20	793	1121	13.6	19.3	192
M1D2	4.4×10^{-5}	232	859	925	2.7	6.0	96.0
M2D1	4.4×10^{-5}	379	787	838	1.9	4.0	75.8
M2D2	4.4×10^{-5}	491	699	747	1.4	4.1	74.4
M3D1	4.4×10^{-4}	232	894	949	2.2	5.3	91.3
M4D1	4.4×10^{-4}	538	716	760	0.9	4.9	87.3
M4D2*	4.4×10^{-4}	649	501	527	1.3	3.8	59.5
M5D1	4.4×10^{-3}	232	880	957	2.6	5.9	97.5
M5D2	4.4×10^{-3}	379	782	867	1.1	3.3	75.9
M6D1	4.4×10^{-3}	538	673	688	0.6	3.3	66.7
M6D2*	4.4×10^{-3}	649	524	545	0.9	3.7	60.4
Irradiation Temperature = 452°C							
M1I1	4.4×10^{-5}	20	749	870	12.4	18.1	157
M1I2	4.4×10^{-5}	232	707	778	5.6	8.3	103.2
M2I1	4.4×10^{-5}	452	731	829	4.4	7.1	102.0
M2I2	4.4×10^{-5}	563	621	659	1.4	3.4	63.1
M3I1	4.4×10^{-4}	232	834	938	7.7	10.5	128.8
M3I2	4.4×10^{-4}	427	724	801	6.3	9.3	113.6
M4I1	4.4×10^{-4}	538	612	652	2.1	4.0	67.1
M4I2*	4.4×10^{-4}	649	414	448	1.6	3.8	55.1
M5I1	4.4×10^{-3}	232	832	921	6.8	9.1	118.2
M5I2	4.4×10^{-3}	452	728	775	2.0	4.0	73.1
M6I1	4.4×10^{-3}	538	633	681	4.2	6.6	88.0
M6I2*	4.4×10^{-3}	649	448	525	3.2	6.2	77.5

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* Possibly intergranular failure.

$$n = \ln(\sigma_u/\sigma_y) \ / \ \ln(E \ \varepsilon_u/\sigma_y) \qquad (3)$$

where σ_u and ε_u are the true ultimate stress and true uniform strain. In these irradiated specimens n is small, on the order of 0.03.

5. RESULTS

The values of fracture toughness predicted by Equation 1 are shown in Table 1. Some entries in Table 1 are designated by a star, representing tensile tests carried out at temperatures sufficiently high that failure is expected to be intergranular. For these cases, the correlation is not expected to be applicable. Figure 2 shows a comparison of the toughness data of Huang and Wire and the predictions of this correlation using tensile data from Table 1 for irradiation at 379°C. Also shown are predictions of toughness at 593°C for the two notched specimens reported by Huang and Fish.[3]

The agreement between actual toughness measurements and predictions based on tensile data is quite good; both exhibit a similar dependence

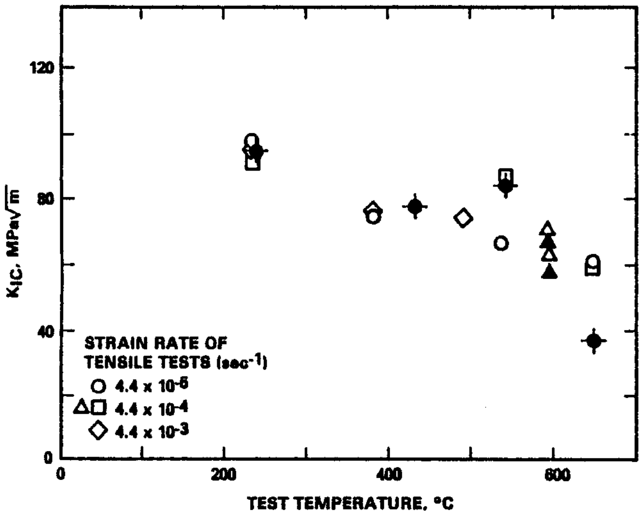

FIGURE 2
Comparison of Tensile-Based Predictions for an Irradiation Temperature of 379°C with Toughness Data (solid symbols) irradiated at 375-415°C.

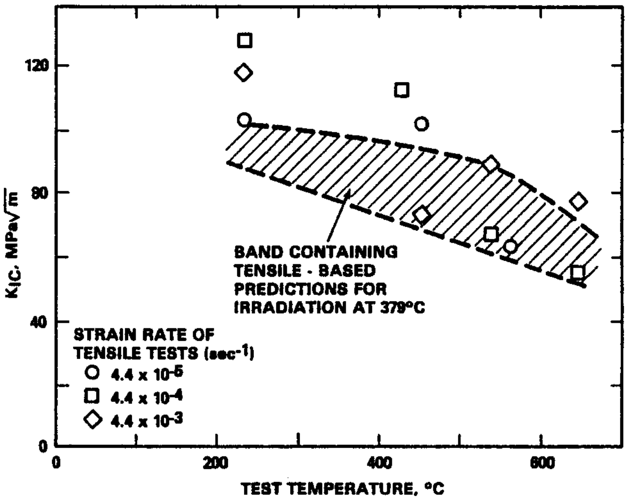

FIGURE 3
Comparison of Toughness Predictions for Irradiations Conducted at 379°C (Data Band) and 452°C (Data Points).

on test temperature. The data of Huang and Fish suggest a slight dependence of toughness on irradiation temperature. The agreement in Fig. 1 of data and predictions at both 7.8 and 11.0 x 10^{22} n/cm^2 suggests that fracture toughness at 400°C saturates at relatively low fluence and does not decline thereafter.

To explore the possibility of a toughness dependence on irradiation temperature, the tensile data from specimens irradiated at 452°C were used to make predictions of toughness. Figure 3 shows that a sensitivity to irradiation temperature is indeed predicted, and is strongest for tests conducted below the irradiation temperature.

6. DISCUSSION

Since toughness data are available for only a limited range of irradiation temperatures, there is no opportunity at present to test the general applicability of this correlation to a wider range of irradiation conditions. It is fortunate, however, that the successful correlation at 379°C employs two convenient and easy-to-measure parameters, grain size and total elongation. If this correlation is valid rather than fortuitous, a rationale is required for the relevance of these parameters to this model and this material.

There has been no definitive guidance for selection of these parameters. Krafft originally suggested uniform elongation but Schwalbe and Backfisch assumed that logarithmic fracture strain based on reduction of area "represents a reasonable measure." The superiority of either of these over total elongation cannot be established, and the chief virtue of the latter is its apparent success.

Both Krafft and Schwalbe agreed, however, that whatever critical strain parameter was chosen, it should correspond to some appropriate microstructural feature which defines a process zone size. Krafft used toughness and tensile data to calculate apparent process zone sizes and concluded that for soft and medium strength materials the zone size was smaller than the grain size. For a high strength material he found the zone size to be on the order of the grain size. AISI 316 irradiated and tested at ~400°C has a yield strength of ~800 MPa[9] and therefore qualifies as a high strength material. Schwalbe and Backfisch focused on softer materials with hard inclusions that served as void nucleation sites and specified the dimple diameter on the fracture surface as the process zone size.

In irradiated 316 stainless steel the grain interior is hardened extensively by high densities of small voids, precipitates and Frank loops.[9] Grain boundaries are relatively free of these smaller obstacles but larger η-silicide precipitates are present at the boundaries[10] which may serve as crack nucleation sites. Huang[5] notes that plate-like or "channel" fracture surfaces occur in these specimens. These surfaces are dominated by facets, which approach the grain size for tests at 538°C. Channel fracture has been observed in irradiated AISI 304[11,12] and has been shown to result from channeling of dislocation activity through narrow deformation zones. Distortion of irradiation-induced voids within these zones leads to local strain estimates of several hundred percent. When these zones intersect grain boundaries, crack nucleation is a potential consequence.

The presence of flow localization of this type apparently does not invalidate the use of a fracture model which assumes that deformation around the crack tip can be described by the macroscopic deformation law for plasticity. The reason why the Krafft model appears to work is probably that the extent of the plastic zone (estimated to be ~2 mm) is much larger than the microscopic scale of flow localization. Thus the stress relaxation invoked by this model occurs over a dimension in which only the average strain is important.

7. CONCLUSIONS

It appears that a correlation between fracture toughness and tensile properties may exist for AISI 316, thus allowing the use of easily obtained tensile data for estimation of toughness decreases induced by irradiation.

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