FRACTURE TOUGHNESS OF PRESSURE VESSEL STEELS
FROM SMALL SPECIMENS

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The use of fracture mechanics in the fracture-safe design and continued safe operation of reactor pressure vessels has provided an incentive for the development of small specimens for obtaining pertinent fracture toughness data. Small specimens are required for economic reasons (when a large number of heats are involved) and for space limitation reasons (such as in surveillance programs). Several approaches to obtaining fracture toughness from small specimens by either direct measurements or indirect correlations and calculations, are reviewed, and their merits and limitations are discussed. Emphasis is placed on techniques which have been developed to determine static and dynamic fracture toughness from surveillance-type specimens. Recently developed techniques for obtaining dynamic J-initiation values from a single test specimen and methods for estimating lower and upper shelf fracture toughness from tensile properties are also presented.
1. **Introduction**

Recent fracture safe design criteria based upon a fracture mechanics methodology have resulted in improved safety and reliability of structural components. However, the often prohibitive cost due to the large number of heats of materials involved and specimen size limitations have provided an incentive for developing inexpensive, small specimen fracture mechanics information for quality control and surveillance applications. Using mechanical properties measurements from small test specimens either directly, or indirectly in a correlative manner, can produce estimates of fracture mechanics parameters. This paper reviews several approaches that we have taken for obtaining static and dynamic fracture toughness from small, surveillance-type specimens of nuclear pressure vessel steels. The direct methods for obtaining fracture toughness data will be discussed first.

2. **Precracked Charpy Measurements**

Since the logical extension of the standard Charpy test is to pattern a normal fracture mechanics test by fatigue precracking the Charpy specimen, initial studies were concerned with establishing direct measurement limitations for the precracked Charpy test. For impact loading, testing procedures were developed under sponsorship of the Electric Power Research Institute (EPRI) to ensure reliable results [1]. Limitations due to fracture mode and specimen size were also investigated and criteria were established for both linear elastic and elastic-plastic fracture for both cleavage and fibrous initiated fracture [2].

2.1 **Cleavage Initiated Fracture**

Small specimens of nuclear pressure vessel steel fail in the linear elastic regime by slip-initiated cleavage fracture (except at extremely low temperatures). Limits for linear elastic behavior are simply based on fracture before general yielding and values of $K_{IC}$ up to approximately 60 MN-m$^{-3/2}$ can be calculated directly (Fig. 1). At temperatures above where general yielding occurs ($T_{GY}$), fracture can still be predominantly cleavage initiated and an elastic-plastic measurement of specimen energy converted to a $J_{IC}$ (and to an equivalent $K_{JC}$) is made.

Generally, elastic-plastic $K_{JC}$ values of up to 130 MN-m$^{-3/2}$ provide reliable toughness measures by merely using maximum load (cleavage load drop) as the point of fracture initiation, i.e., $J_{max} = J_{IC} \times (K_{Jm} = K_{JC})$. Above this toughness level which corresponds to the 25J/$\sigma_y$ level ($\sigma_y$ is the material flow stress), a specimen-size restriction for cleavage initiated fracture is needed or stable crack growth (fibrous initiation) occurs prior to maximum load at temperatures greater than $T_{CL}$. In either case, $J_{max}$ is greater than the true $J_{IC}$. Thus, the equivalent stress intensity values are nonconservative; in particular, equivalent energy fracture toughness measurements based upon maximum load (which have been shown to be equal to $K_{Jm}$ [3]) can be overly optimistic by up to 20 percent or more.

2.2 **Fibrous Initiated Fracture**

Because of the nonconservatism of maximum load elastic-plastic measures of fracture toughness for fibrous initiated fracture, $J_{IC}$ values are determined from unloading compliance and crack growth curves (often termed R-curves for convenience). However, since dynamic $J_{IC}$ cannot be determined using the compliance technique, dynamic R-curves were generated using an instrumented drop tower and hardened steel stop blocks to stop the specimen deflection. Dynamic $J_{IC}$ values were determined from the R-curves based upon a regression analysis of the data and the definition of a blunting line ($J/2\sigma_y$) for stress intensity rates of approximately
$3 \times 10^5 \text{ MNm}^{-3/2} \text{s}^{-1}$. Results for static and intermediate rate loading were also obtained, and it was found that dynamic initiation toughness on the upper shelf was almost always greater than the static toughness [4]. Fig. 2 illustrates the effect of loading rate on $K_{IC}$. Note that dynamic toughness is not always the most conservative value. The commonly used specimen size criterion of $50J/\sigma_F^2$ may limit the validity of the $J_{IC}$ values obtained from small specimens [2] (Fig. 1).

3. Side-Grooved Precracked Charpy Tests

Generating R-curves is not feasible for a limited number of irradiated surveillance specimens. Therefore, a single-specimen technique was utilized for determining $J$-integral initiation values. Following the work of Green and Knott for mild steel [5], precracked Charpy specimens were side-grooved, forcing fibrous initiation to occur nearer to maximum load. Results for standard size precracked Charpy specimens (original thickness, $B$, equal to 10 mm) and over-sized precracked Charpy bars (remaining net thickness, $B_o$, equal to 10 mm) are shown in Figs. 3 and 4 for static loading of SA302B and dynamic loading of SA533B-1, respectively.

Side-grooving to a depth of 30% (15% on each side) caused fibrous initiation to occur at maximum load, and thus $J_{max} = J_{IC}$ using the net section thickness to calculate $J$. There does appear to be a remaining ligament depth ($b$) size requirement for higher toughness material tested under quasi-static loading; this requirement, when violated however, produces conservative measures of $J_{IC}$ [6].

4. Critical Fracture Stress and Fracture Strain Models

Several indirect methods for obtaining predictions of fracture toughness from surveillance-type specimens were also investigated. The method described in this section involves the use of simple uniaxial mechanical properties as related to different fracture models depending upon the failure mode. Failure at the lower shelf has been modeled as slip-initiated cleavage fracture using the critical stress criterion proposed by Ritchie, Knott, and Rice (RKR) [7]. In a similar manner, failure at the upper shelf has been modeled as fully ductile rupture (microvoid coalescence) using a critical strain criterion originally proposed by McClintock [8]. The application of these models involved determination of critical stress and strain values from bend and notched tensile tests, knowledge of precise analyses for the elastic-plastic stress and strain distributions ahead of sharp cracks, and an examination of the microstructurally-significant size-scale controlling fracture (such as some multiple of the grain size or inter-particle spacing).

Predicted values of static, dynamic, and irradiated cleavage initiated fracture toughness agreed with experimental values for temperatures slightly beyond the Nil Ductility Transition Temperature. Combining the two models allowed the full $K_{IC}$-temperature transition to be predicted. Fig. 5 illustrates the model predictions for SA533B-1 steel in the unirradiated condition, and Fig. 6 shows the critical stress model predictions for several irradiated conditions [9].

5. Specimen Strength Ratio

Empirical correlations for estimating fracture toughness from small specimens were also investigated. The specimen strength ratio ($R_s$) determined from small specimens correlated well with $K_{IC}$ for $R_s < 2.0$ for a variety of loading rates and specimen sizes [10]. Conservative estimates of cleavage initiated, elastic-plastic fracture toughness can extend beyond
$R_g$ values of 2.0. The ASTM E399 size requirement appears to be too restrictive for the class of steel studied, and a more appropriate requirement would reduce the current requirement by a factor of four. Fig. 7 shows the correlation (for nine heats of SA533B-1 steel) of impact $K_{lc}$ results from 25.4 mm thick bend specimens with impact $R_{ab}$ values from precracked Charpy tests.

6. Concluding Remarks

As a result of this EPRI sponsored research, new options are available to the reactor vendors and utilities for obtaining fracture toughness from surveillance-type specimens. Future work involving statistically-based correlations derived from over fifty heats of pressure vessel steel should lead to direct Charpy V-notch energy - $K_{lc}$ correlations with a known degree of reliability.

References


Fig. 1. Schematic of Measurement (Size) and Fracture Mode Limitations of Preqcracked Charpy Specimens for a Typical SA533B-1 Steel.

Fig. 2. Influence of Loading Rate on Fracture Toughness.

Fig. 3. Side-Groove Results for Static Bend Tests on SA302B Steel at 71°C.

Fig. 4. Side-Groove Results for Impact Bend Tests on SA533B-1 Steel at 71°C.
Fig. 5. Variation of Static Fracture Toughness with Temperature for Unirradiated SA533B-1 Steel as Compared to Critical Stress (Upper Shelf) and Critical Strain (Lower Shelf) Predictions.

Fig. 6. Critical Stress Model Predictions of Radiation Effects on Lower Shelf Fracture Toughness Compared with Experimental Data on Neutron Irradiated SA533B-1.

Fig. 7. Correlation of Impact $K_{IC}$ Values for 25.4 mm Thickness Bend Specimens With Impact $R_{IC}$ From Precracked Charpy Tests.