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# Determination of the Toughness of In-Service Steam Turbine Disks Using Small Punch Testing

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**Knowledge of the material toughness is crucial in assessing the integrity of heavy section steel components. Conventional tests to determine the toughness involve extraction of large blocks of material and therefore are not practical on in-service components. On the other hand, conservative assumptions regarding toughness without regard to actual data can lead to expensive and premature replacement of the components. Previous EPRI studies have demonstrated the use of a relatively nondestructive technique termed the "small punch test" to estimate the fracture appearance transition temperature (FATT) and fracture toughness ($K_{Ic}$) of high-temperature turbine rotor steels and nuclear reactor pressure vessel steels. This paper summarizes the results of research into the feasibility of extending the small punch test to characterize the toughness of the 3 to 3.5% NiCrMoV (3-3.5NiCrMoV) low alloy steel used for fossil and nuclear power plant low-pressure (LP) steam turbine disks. Results of the present study show that the small punch transition temperature, $T_{sp}$, is linearly correlated with FATT, so that measurement of $T_{sp}$ permits estimation of the standard Charpy FATT through empirical use of the correlation. The statistical confidence prediction uncertainty bands for the correlation were found to be narrow enough to make the small punch- based FATT estimation practical for this alloy. Additionally, independent $T_{sp}$ measurements made by PowerGen, UK, on some of the same test materials were in excellent agreement with measurements made here, indicating that the small punch $T_{sp}$ measurement can be reproducible across laboratories. Limited testing for fracture initiation toughness showed, as has been demonstrated for other materials, that the small punch test-based initiation fracture toughness ($K_{Ic}$) determination was within ±25% of the ASTM standard measurement of $K_{Ic}$, suggesting that the test method can be used for direct determination of fracture initiation toughness.**

**Keywords** disk, miniature sample, steel, testing, toughness, turbine

## 1. Introduction and Background

The risk of catastrophic rupture of an operating component is a function of the tolerable size of flaw or defect, which, in turn, is directly and quantitatively related to the component material fracture toughness, $K_{Ic}$ (or $J_{Ic}$). In many cases, particularly with low-alloy steel components in the electric power generation industry, the common practice for limiting this risk has largely been one whereby operation is conservatively and simply constrained such that significant operating stresses are only permitted at component temperatures approaching or exceeding the material fracture appearance transition temperature (FATT) or temperature at which the standard Charpy impact specimen fracture transitions from an apparently brittle to a ductile mode. A rotor prewarming requirement on a high-pressure steam turbine startup is an example of such constrained practice. The constrained practice is essentially supported by the observation that the flaw tolerance, *i.e.*, fracture toughness, $K_{Ic}$, can be related to FATT *via* empirical correlations (*e.g.*, Reference 1). However, two sources of the uncertainty of material properties contribute to a level of operating conservatism that may be excessive and prohibitively costly.

- The material FATT is unknown because (a) original material test records are unavailable, (b) FATT was never measured, (c) in-service embrittling mechanisms (*e.g.*, temper embrittlement) have produced an unknown level of embrittlement, or (d) FATT at a specific location of concern (such as flaw location) cannot be reliably estimated due to unknown spatial variation in FATT.
- The empirical correlation between FATT and fracture toughness, $K_{Ic}$, is uncertain, and therefore interpreted conservatively (lower-bound $K_{Ic}$ estimated from $K_{Ic}$—excess temperature correlation data).

Ideally, accurate estimation or measurement of material fracture toughness, $K_{Ic}$, is desirable for the location of interest. The significant volume of sample material required for conventional measurement of $K_{Ic}$ or FATT, however, makes application of the direct testing approach impractical in the case of many in-service components. At best, sampling and conventional testing of material may be accomplished typically at locations where large enough volumes of material can be removed without compromising component integrity. However, the approach suffers from the need to extrapolate measured properties to the location of concern. Moreover, the extrapolation can be large and relatively uncertain in some cases.

The development and in-service application of essentially nondestructive, miniature material sample removal systems (*e.g.*, the surface sampling system, SSam™[2]) provided the

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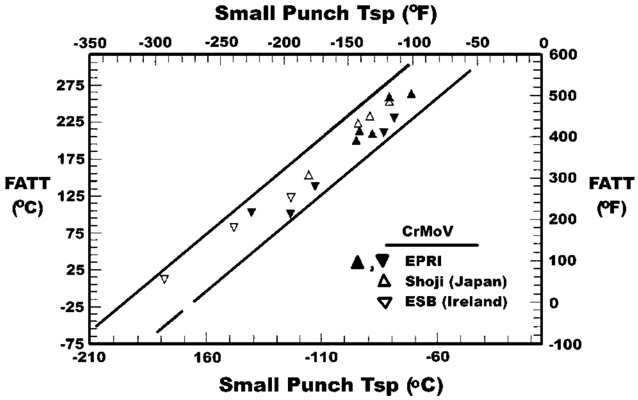

**Fig. 1** Charpy FATT-small punch transition temperature ($T_{sp}$) correlation developed for CrMoV forged low alloy turbine rotor steel; also included are data from Shoji (Japan) and the Electricity Supply Board (ESB, Ireland)

practical incentive for development of small specimen test methods to evaluate material toughness. The Electric Power Research Institute (EPRI) has completed development of the small punch (disk-bend) test to determine material fracture properties from miniature specimens (6.4 mm diameter or 0.25 in. by 0.5 mm or 0.020 in. thick). The test method for determination of FATT is empirical, and based on obtaining a correlation between the standard Charpy FATT and the small punch transition temperature, $T_{sp}$, measured in a series of punch tests. Nondestructive, miniature sample removal and small punch testing for evaluating material FATT has been developed and applied to a range of components (*e.g.*, Ref 3 to 5) and will not be discussed here. The reader is referred to these papers for details on the critical aspects of applying this technology to evaluating the condition of in-service turbine generators. More recently, the small punch test has been further developed to directly determine material fracture toughness $K_{Ic}$ (and $J_{Ic}$) from the results of a single SP test.[6] In the past, these techniques have been demonstrated for steels of high-temperature, high-pressure (HP) rotors and of reactor pressure vessels.[7–10] An example of the correlation obtained for an HP rotor steel is shown in Fig. 1. This paper describes the extension of the SP test technique to the 3 to 3.5NiCrMoV grade steel normally used for disks in the low-pressure (LP) steam turbines.

## 2. Description of Small Punch Test and Results Analysis

The small punch test is essentially a punch-and-die loading test method wherein a relatively small, flat (often disk-shaped) specimen is punched with a ball, or hemispherical head, punch. Small punch test specimens have varied in size between 3 and 10 mm (0.12 and 0.40 in.) in diameter and between 0.1 and 0.75 mm (0.004 and 0.030 in.) in thickness. Figure 2 is a schematic cross-sectional view of the punch-and-die test device used throughout all of the EPRI-related work. Note the key dimensions—specimen measures 6.35 mm (0.25 in.) diameter × 0.5 mm (0.020 in.) thickness, punch hemispherical head diameter is 2.5 mm (0.1 in.), and receiving die diameter is 3.8 mm (0.15 in.). The punch advances at a constant displacement rate (typically ~0.25 mm/min or 0.010 in./min), deforming the specimen against the receiving die, while the load is recorded as a function of the punch displacement.

For measurement of the small punch transition temperature, $T_{sp}$, and its correlation with FATT, a series of tests were run for each material. The series consisted of at least six tests at temperatures between liquid nitrogen (−196 °C) and room temperature. The total absorbed energy to the first peak load (peak load defined as load followed by a load drop in excess of 10% of peak), measured as the area under the small punch load-displacement curve, was noted for each test. The (small punch) energy was then plotted against the test temperature, and $T_{sp}$ was determined as the temperature at which the energy level is midway between the upper-shelf and lower-shelf energy levels. The $T_{sp}$ was then plotted as a function of the known values of FATT to develop a correlation curve for the steel.

For determination of fracture toughness ($K_{Ic}$, $J_{Ic}$) at room temperature, two repeat small punch tests were conducted at room temperature for each material investigated. Each test involved development of the load-displacement curve, and identification of crack initiation with respect to the point on the load- displacement curve where the initiation occurs and with respect to where on the test specimen the crack initiates. For identifying crack initiation, a fiberscope-changed coupled device (CCD) camera-video recorder combination system is used. A schematic of the test setup used here and in all of the prior EPRI fossil power plant research is shown in Fig. 3.

The test data were then analyzed using a procedure described elsewhere (*e.g.*, Ref 6 and 9). The procedure essentially involves computing the critical strain energy density at the location of crack initiation on the small punch specimen, using finite element analysis. This strain energy density is then computed, also by finite element stress analysis, at the crack tip of a plane-strain compact tension specimen, “analytically” loaded. Initiation toughness is next estimated *via* a handbook *J*-integral solution at the load level for which the crack-tip energy density just equals the critical small punch-measured strain energy density.

The above procedure requires determination of the stress-strain constitutive behavior of the material. The constitutive behavior is assumed to be Ramberg-Osgood, power law hardening, and the power law constants are determined from the observed load-displacement behavior by an optimal fitting technique detailed elsewhere (*e.g.*, Ref. 6 and 9). In effect, the procedure produces an estimate of the (tensile) stress-strain behavior of the material at the test temperature.

## 3. Test Materials

A list of steels tested and their FATT values are summarized in Table 1. In Table 1, the steels identified as A1-D3, A1-D4, and A1-D6 have an average reported weight percent composition of 3.2% Ni, 0.75% Cr, 0.37% Mo, and 0.14% V. Material A1-D8 has a nominal reported composition of 4.3% Ni, 1.4% Cr, 0.50% Mo, and 0.21% V. Nominal compositions of the remaining alloys are as follows—VH1: 2.95% Ni, 0.65% Cr, and 0.31% Mo; VH2: 2.9% Ni, 0.61% Cr, and 0.26% Mo; and VH3: 3.5% Ni, 1.38% Cr, and 0.41% Mo. The A1-D materials and the

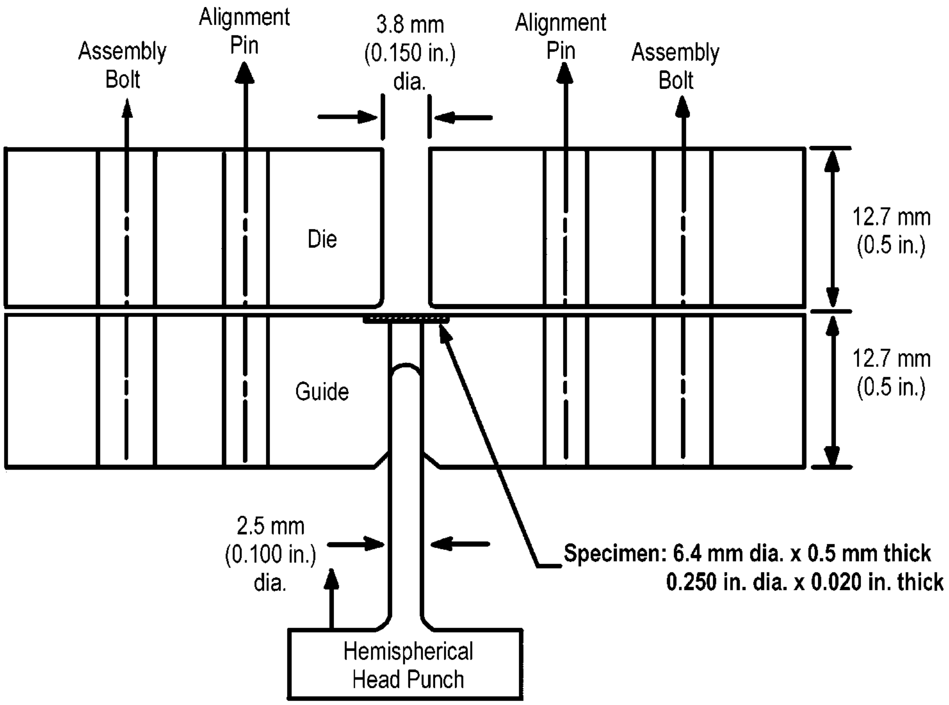

**Fig. 2** Schematic of small punch test

VH1 and VH2 materials are from ex-service LP turbine disks. The VH3 material is from an unused LP rotor forging.

The reported data of Table 2 represent an average of two tests for A1-D3 (reported $J_{Ic}$ = 57 and 70 kJ/m$^2$) and multiple tests (number not reported) on VH1-AR, exhibiting toughness in the range 61 to 175 $\text{MPa}\sqrt{\text{m}}$, with a mean of 100 $\text{MPa}\sqrt{\text{m}}$. The material identifiers of Table 2 are identical to those of Table 1. The test specimen geometry is standard 1T-CT (1 in. thick compact tension) for the VH1 material, and 11 mm thick, three-point bend for the A1-D3 material.

The A1-D3 material reportedly exhibited fully ductile fracture behavior, whereas the VH1-AR material exhibited cleavage fracture at the maximum load and corresponding $K_I$ levels (reported as $K_{Ic}$). The VH1-AR material tests reportedly exhibited less than 0.2 mm stable crack extension before cleavage, so that the reported toughness based on maximum load in this case roughly represents the true initiation toughness, $K_{Ic}$.

## 4. Results and Conclusions

### 4.1 Small Punch Transition Temperature, $T_{sp}$, and FATT

Figure 4 illustrates a typical example of the small punch energy-temperature data that have been used in determination of the transition temperature, $T_{sp}$. Table 1 summarizes the measured $T_{sp}$ values along with the corresponding reported Charpy FATT for each of the materials for all ten test materials.

Figure 5 graphically summarizes the small punch transition temperature ($T_{sp}$)-FATT data and correlation derived therefrom. Included in Figure 5 are small punch test data generated from tests on a similar device and provided by PowerGen, UK, illustrating excellent agreement with the data developed here. The excellent agreement indicates that the measurement of $T_{sp}$ can be highly reproducible from laboratory to laboratory.

Excluding an apparent outlier (VH1-SC), reasons for which are currently not known, the data showed a good linear correlation obtained by regression as

$$\text{FATT (°C)} = 259.8 + 1.731\ T_{sp}\ \text{(°C)}$$

$$\text{FATT (°F)} = 444.3 + 1.731\ T_{sp}\ \text{(°F)}$$

with a regression coefficient of 0.89.

The 90% confidence statistical upper- and lower-prediction bounds are also represented on the graph.

Several conclusions are drawn from the results summarized in Figure 5.

- There is an observed linear correlation (regression coefficient = 0.89) between the small punch transition temperature, $T_{sp}$, and the standard Charpy FATT for the 3 to 3.5NiCrMoV turbine steel.
- The width of the 90% confidence statistical prediction bounds indicates that the predictive uncertainty in use of the correlation for estimating FATT from $T_{sp}$ is approximately ±35 °C (±63 °F), comparable to the correlation developed for CrMoV currently in use for high pressure/intermediate pressure (HP/IP) turbine rotor FATT estimation, and narrow enough to make this a practical, usable approach for the estimation of LP turbine 3-3.5NiCrMoV steel FATT.

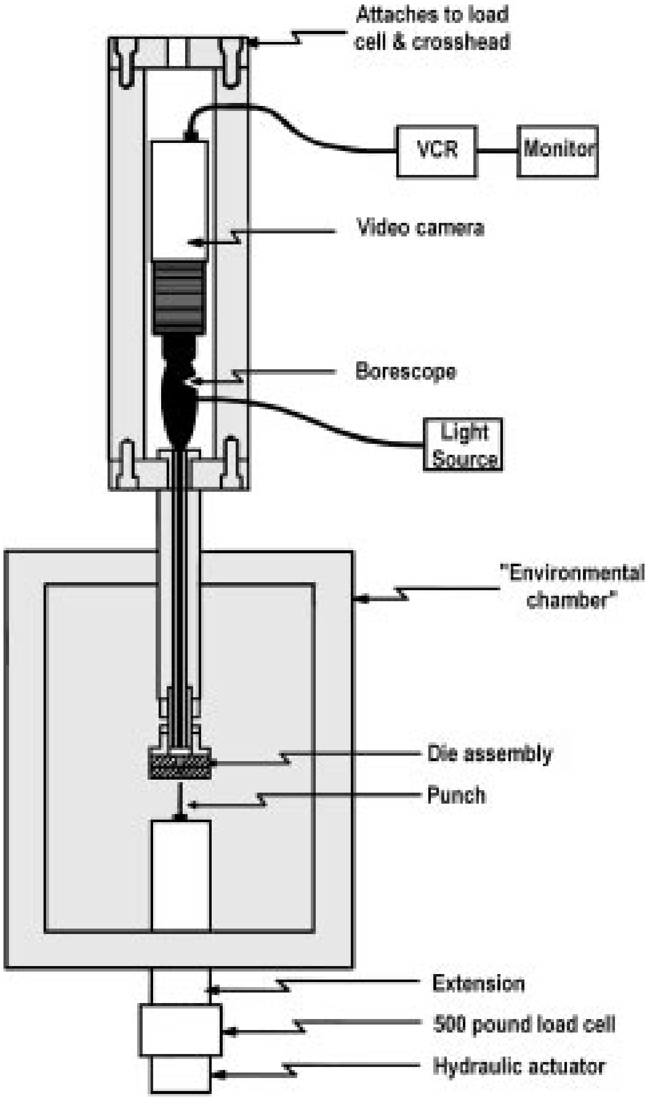

**Fig. 3** Schematic of small punch test setup used for direct fracture toughness determination; note arrangement for identifying crack initiation on the convex or bulged side of the test specimen

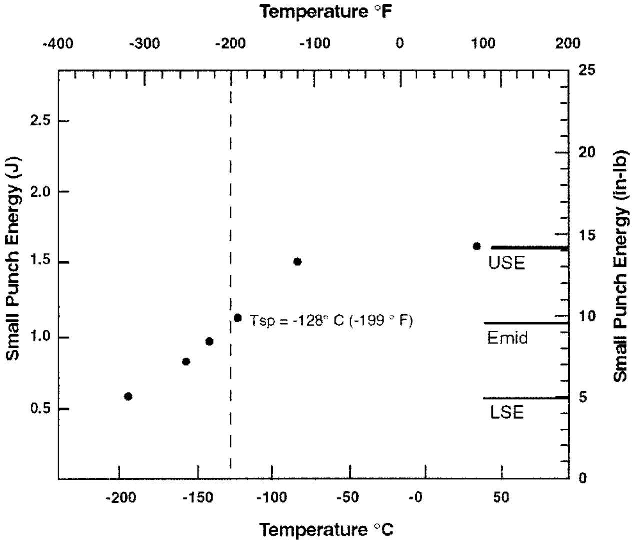

**Fig. 4** Example of an energy vs test temperature curve for steel A1-D8 illustrating the method for determining the transition temperature $T_{sp}$

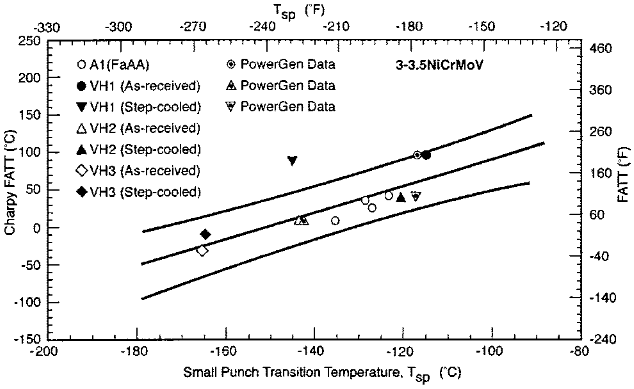

**Fig. 5** Small punch transition temperature, $T_{sp}$, vs standard Charpy FATT; included are data provided by PowerGen, UK. Solid lines are the best-fit linear correlation and 90% confidence statistical upper-and lower-prediction bounds

**Table 1 Summary of measured $T_{sp}$ and reported Charpy FATT**

| Material | A1-D3 | A1-D4 | A1-D6 | A1-D8 | VH1-AR(a) | VH2-AR | VH1-SC(b) | VH2-SC | VH3-AR | VH3-SC |
|---|---|---|---|---|---|---|---|---|---|---|
| FATT | 42 | 26 | 9 | 36 | 97 | 9 | 89 | 40 | −30 | −8 |
| °C (°F) | (108) | (79) | (48) | (97) | (207) | (48) | (192) | (104) | (−22) | (18) |
| $T_{sp}$ | −123 | −127 | −135 | −128 | −115 | −144 | −144 | −121 | −166 | −165 |
| °C (°F) | (−190) | (−197) | (−211) | (−199) | (−174) | (−227) | (−228) | (−185) | (−266) | (−265) |

(a) AR: as-received
(b) SC: step-cool embrittled

- The prediction band width (uncertainty) is significantly narrower than that observed for a wider range of compositions of the same NiCrMoV alloy,[7] suggesting that development of similar correlations is better achieved over a restricted range of compositions for a given alloy.

The excellent agreement between the $T_{sp}$ data generated here and those generated and provided by PowerGen, UK, illustrates that the method can be highly reproducible from laboratory to laboratory for a similar specimen design and test setup.

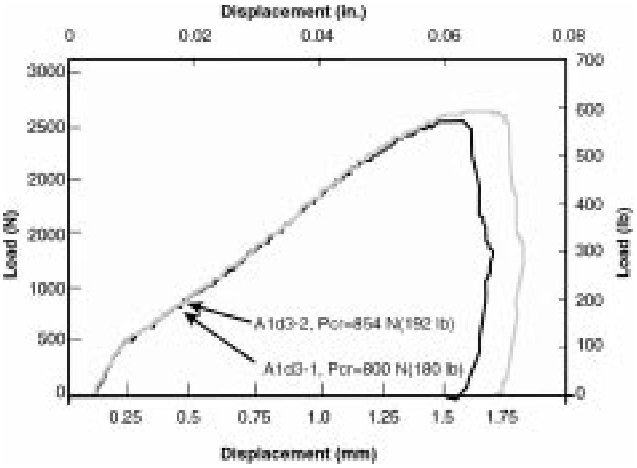

**Fig. 6** Example of a load vs replacement curve for steel A1-D3. Pcr indicates the point of crack initiation. Results of duplicate tests are plotted and the curves are reproducible

**Table 2 3–3.5NiCrMoV turbine steels tested for fracture toughness ($K_{Ic}$, $J_{Ic}$)**

| Material | A1-D3 | VH1-AR(a) |
|---|---|---|
| $J_{Ic}$ kJ/m$^2$ (in.-lb/in.$^2$) | 63.5 (363) | Not measured |
| $K_{Ic}$ MPa$\sqrt{m}$ (ksi$\sqrt{in.}$) | 122 (111)(b) | 100 (91) |

(a) AR: as-received
(b) Estimated from $J_{Ic}$

### 4.2 Fracture Toughness ($K_{Ic}$, $J_{Ic}$)

Figure 6 graphically illustrates the type of load-displacement curves and observed crack initiation points on the curves for steel A1-D3. Table 3 summarizes all of the analysis results using the procedure detailed elsewhere (*e.g.*, Ref. 6 and 9).

Figure 7 graphically summarizes the data along with the EPRI data obtained previously for other steels. The small punch test determinations of $K_{Ic}$ appear to be within ±25% of the ASTM standard mean values, where the ASTM standard test clearly measures initiation toughness. This has been generally observed in previous research[6,9,10,11,12] on a variety of steels. Note that the VH1-AR "ASTM Standard" tests reportedly fractured by cleavage, but exhibited less than 0.2 mm stable crack extension before cleavage, so that the reported toughness based on maximum load in this case roughly represents the true initiation toughness, $K_{Ic}$.

The determination of cleavage toughness, $K_{Jc}$, in the slow-bend transition region is of much interest and relevance, particularly in the nuclear power industry, and EPRI is considering extension of the small punch test capability to determine $K_{Jc}$. EPRI's most recent research[11] has shown, to a limited extent, that the current small punch test interpretation procedure may produce reasonable estimates of $K_{Jc}$ at temperatures near the ASTM Standard E1921[13] reference temperature, $T_o$ (at $K_{Jc}$ levels of roughly 100 MPa$\sqrt{m}$).

The following conclusions may be drawn from the results summarized in Table 3 and Figure 7.

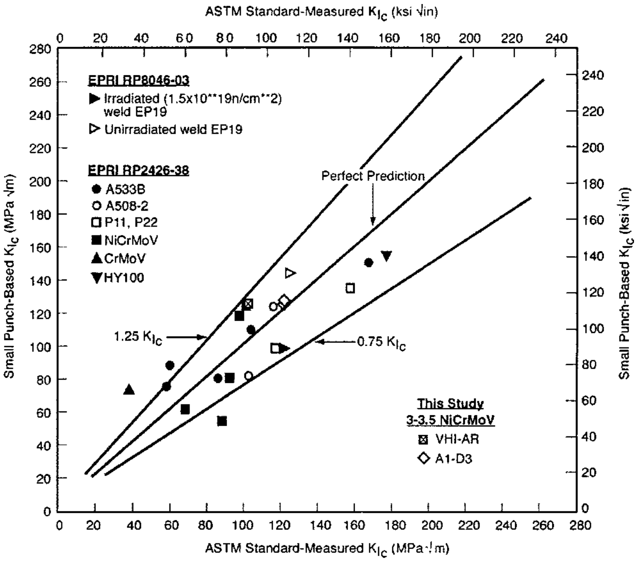

**Fig. 7** Results of prior EPRI research showing the small punch test-based $K_{Ic}$ determination as compared with conventional, standard (ASTM) test specimen-measured $K_{Ic}$ for a variety of power plant steels with varying toughness levels. Included are the results of this study on 3-3.5 NiCrMoV steel

The EPRI small punch test procedure gave good predictions (within ±25%) of the (ASTM) standard fracture initiation toughness, $K_{Ic}$, for the 3-3.5NiCrMoV steels investigated.

The results are consistent with results of prior EPRI research on a variety of power plant steels, including irradiated nuclear reactor vessel steels.

The current small punch test procedure strictly determines initiation toughness, and may be expected to underpredict toughness defined on the basis of cleavage initiation or other condition (*e.g.*, maximum load) where significant crack extension precedes this condition.

## 5. Summary

This study demonstrated that the small punch test can be used for evaluating the FATT and the fracture initiation toughness of 3-3.5NiCrMoV turbine steel. The following are the specific findings.

- The small punch transition temperature, $T_{sp}$, was linearly correlated with the standard Charpy FATT.
- The $T_{sp}$-FATT correlation data have a relatively narrow 90% statistical confidence prediction band, making the estimation of FATT from measurement of $T_{sp}$ usable for this steel.
- Limited comparison of $T_{sp}$ measured in this study with $T_{sp}$ measured and reported by PowerGen, UK, using a similar test setup showed excellent agreement between the two laboratories; this indicates that the small punch $T_{sp}$ measurement can be highly reproducible from laboratory to laboratory for a similar specimen design and test setup.

**Table 3 Summary of test and analysis results for fracture toughness**

| | Small punch-derived tensile properties | | Small punch fracture properties(a) | | | ASTM test specimen data |
|---|---|---|---|---|---|---|
| Test no. | 0.2% YS MPa (ksi) | UTS MPa (ksi) | $w_{sp}$ $10^3$ kJ/m$^3$ ($10^3$in.-lb/in.$^3$) | $J_{Ic}$ kJ/m$^2$ (in.-lb/in.$^2$) | $K_{Ic}$ MPa$\sqrt{m}$ (ksi$\sqrt{in.}$) | $K_{Ic}$ MPa$\sqrt{m}$ (ksi$\sqrt{in.}$) |
| VH1-AR-1 | 627 (90.9) | 823 (119.4) | 182 (26.33) | 68 (388.1) | 125.4 (114.1) | 100 (91) |
| VH1-AR-2 | 627 (90.9) | 823 (119.4) | 167 (24.22) | 66.5 (379.6) | 124.0 (112.8) | 100 (91) |
| A1-D3-1 | 641 (93.0) | 838 (121.5) | 215 (31.15) | 67 (382.3) | 124.4 (113.2) | 122 (111) |
| A1-D3-2 | 641 (93.0) | 838 (121.5) | 234 (33.99) | 69 (395.7) | 126.6 (115.2) | 122 (111) |

(a) $w_{sp}$ = local strain energy density for crack initiation in the small punch test; $K_{Ic}$ is approximated from $J_{Ic}$

- The small punch test-based initiation fracture toughness ($K_{Ic}$) determination was within ±25% of the ASTM standard measurement of $K_{Ic}$, suggesing that the test method can be used for direct determination of fracture initiation toughness.
- The current small punch test procedure strictly determines initiation toughness, and may be expected to underpredict toughness defined on the basis of cleavage initiation or other condition (*e.g.*, maximum load), where significant crack extension precedes this condition.

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