APPLICATION OF THE NORMALIZATION DATA ANALYSIS TECHNIQUE FOR SINGLE SPECIMEN R-CURVE DETERMINATION

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Why Normalization?

- Allows single specimen R-curve determination in extreme test conditions where unloading compliance or electric potential difference (EPD) use is not possible or undesired:
  - High loading rates
  - Temperatures and environments beyond clip gage capabilities
  - Concerns over influence of periodic unloading or EPD on material behavior

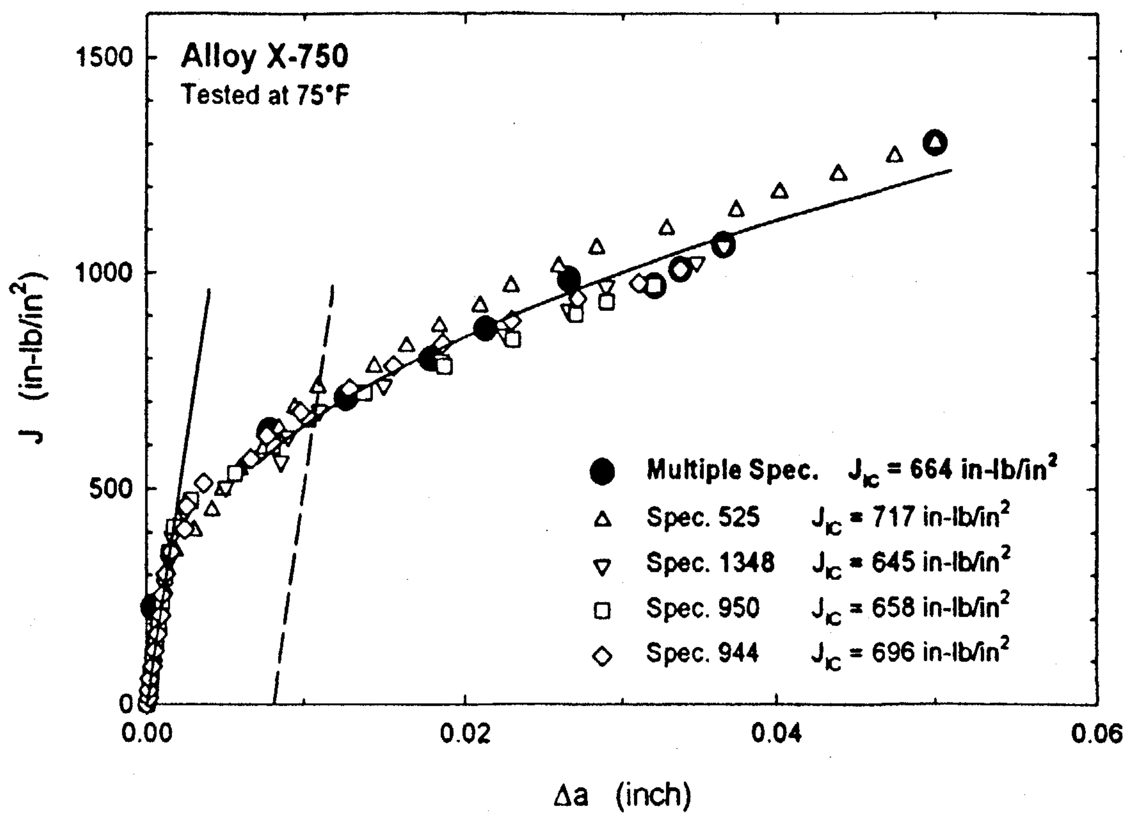
Successful Applications of Normalization Technique

- Comparisons to multi-specimen results
  - X-750 in RT air
  - 316 SS in 1000°F air
  - Alloy 600 in 640°F water
  - A508 Cl. 2 in 480°F water

- Other Materials (in a variety of environments)
  - 17-4 PH, A193 Grade B7, Alloy 690, EN82 and EN52 (weld metals)

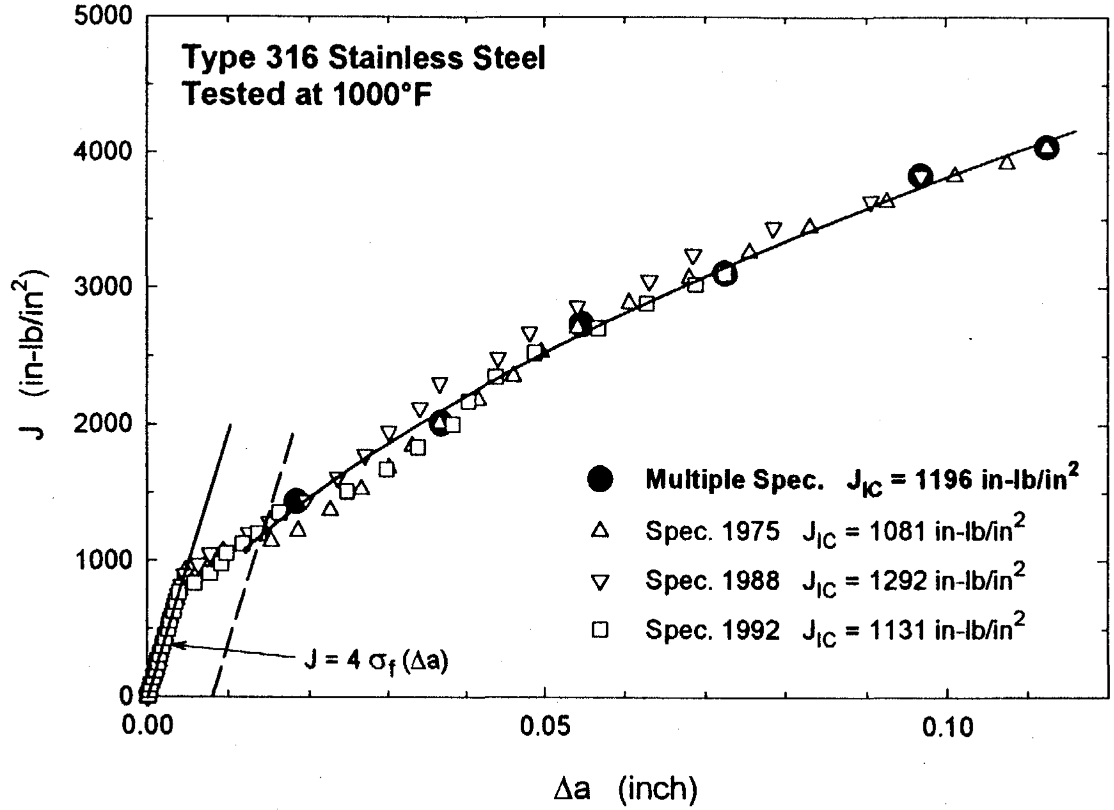
Examples

- Comparison of Normalization R-Curves to Multi-Specimen Data



Examples (cont.)

- Comparison of Normalization R-Curves to Multi-Specimen Data



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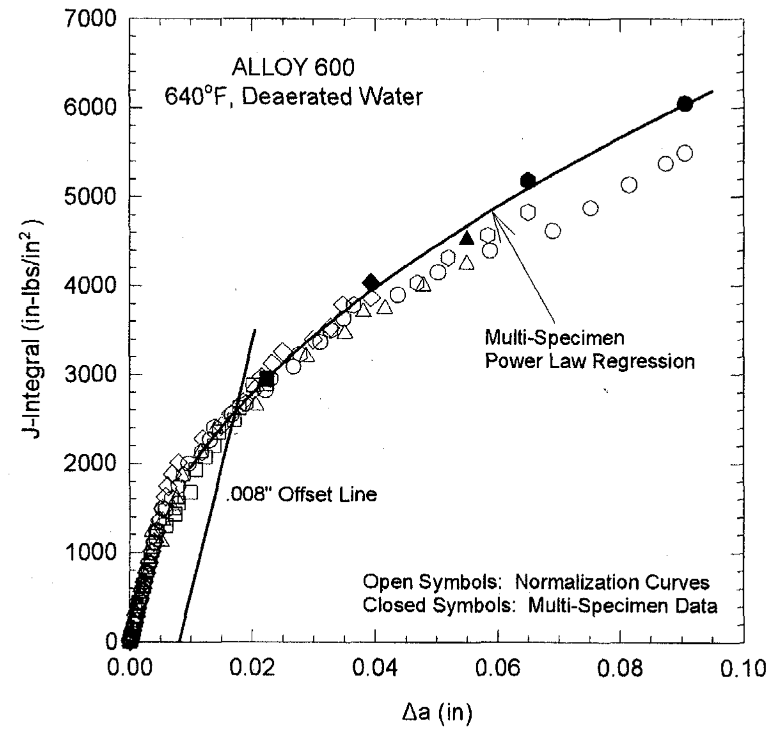
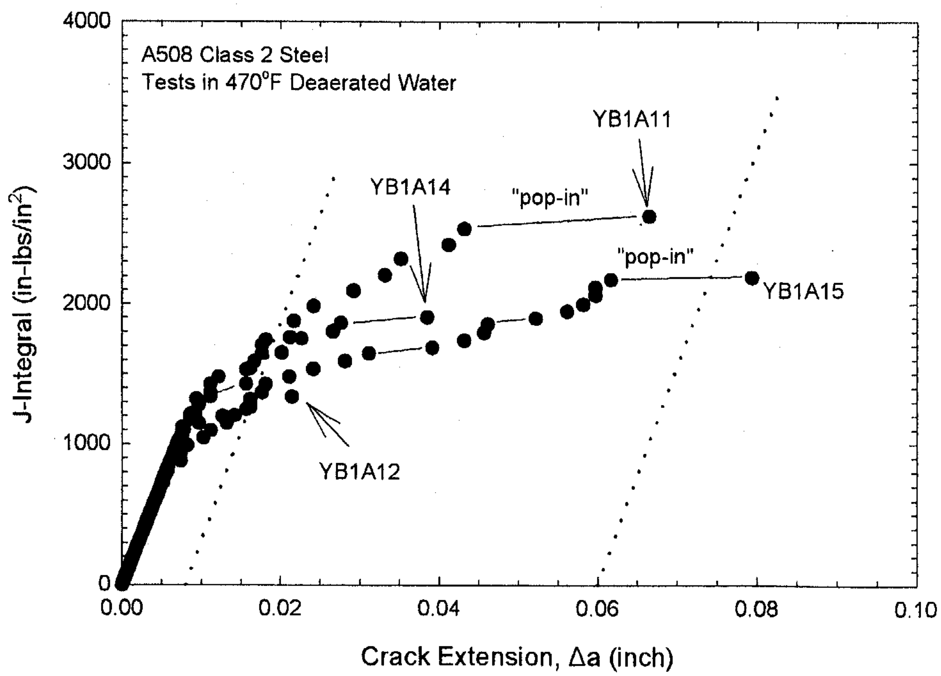
Examples (cont.)

- Comparison of Normalization R-Curves to Multi-Specimen Data



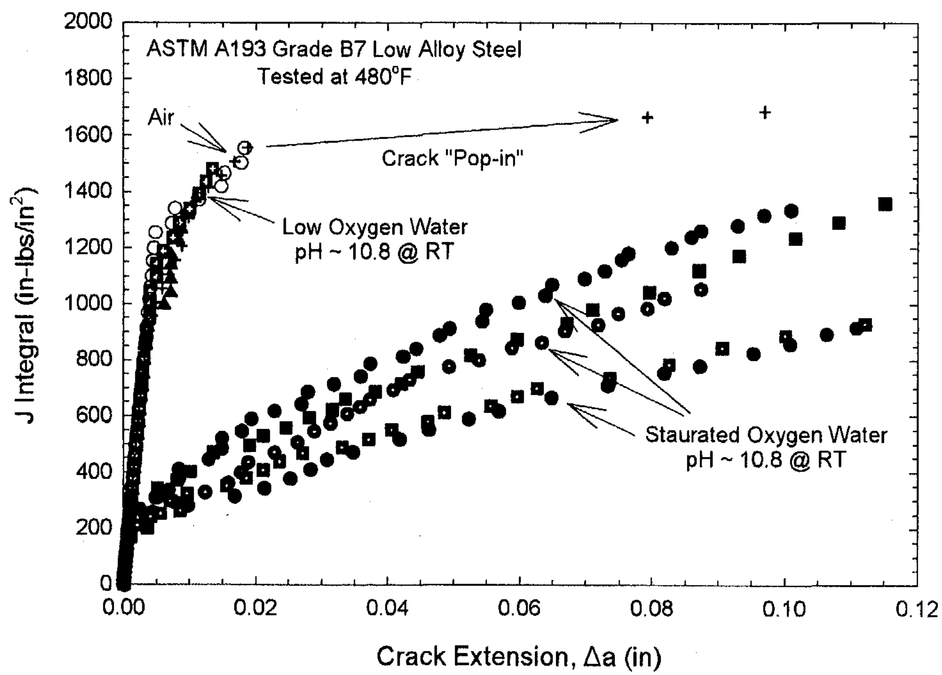
Examples (cont.)

- Characterize pop-in events



Examples (cont.)

- Evaluate environmental effects

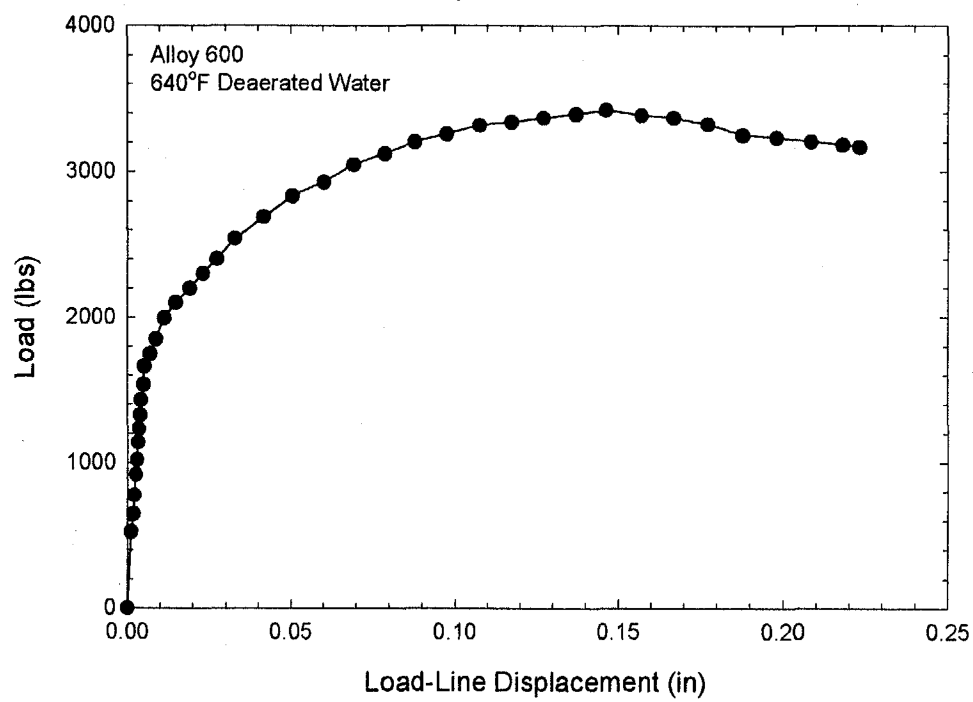


Procedure

- Normalize data based on initial crack length
  - final data point normalized with final crack length
- Estimate initiation point based on straight line tangent from final point to knee of normalization plot
- Fit data from normalized displacement > 10^{-3} to estimated initiation point + final point using the Joyce eqn.
- Iteratively adjust initiation point to achieve best fit of data
- Once initiation point established set subsequent crack tip blunting to initiation value
- Complete process incrementing crack length to fit to curve

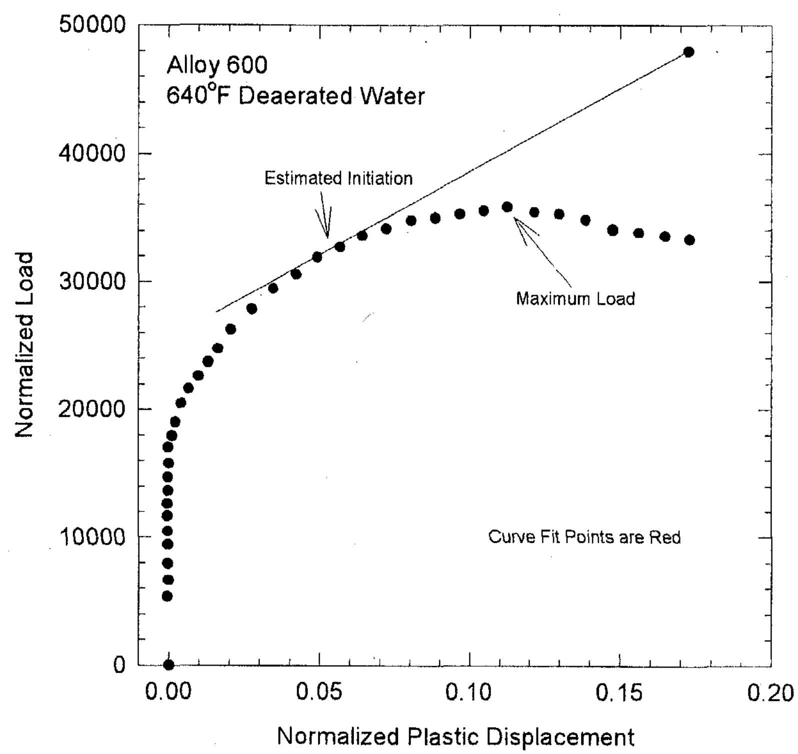
Procedure (cont.)

- Initial load-displacement data



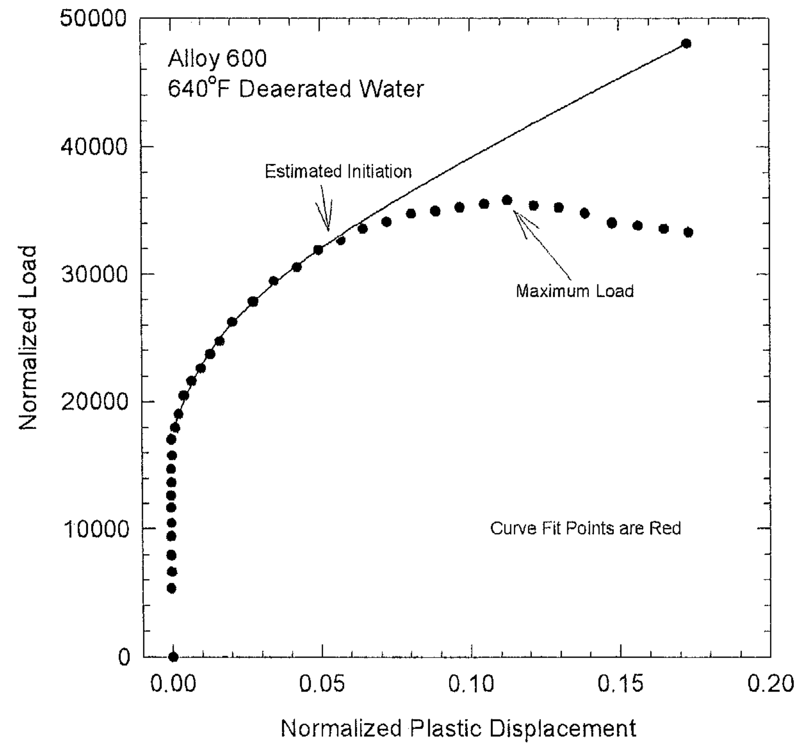
Procedure (cont.)

- Plot uncorrected data/estimate initiation



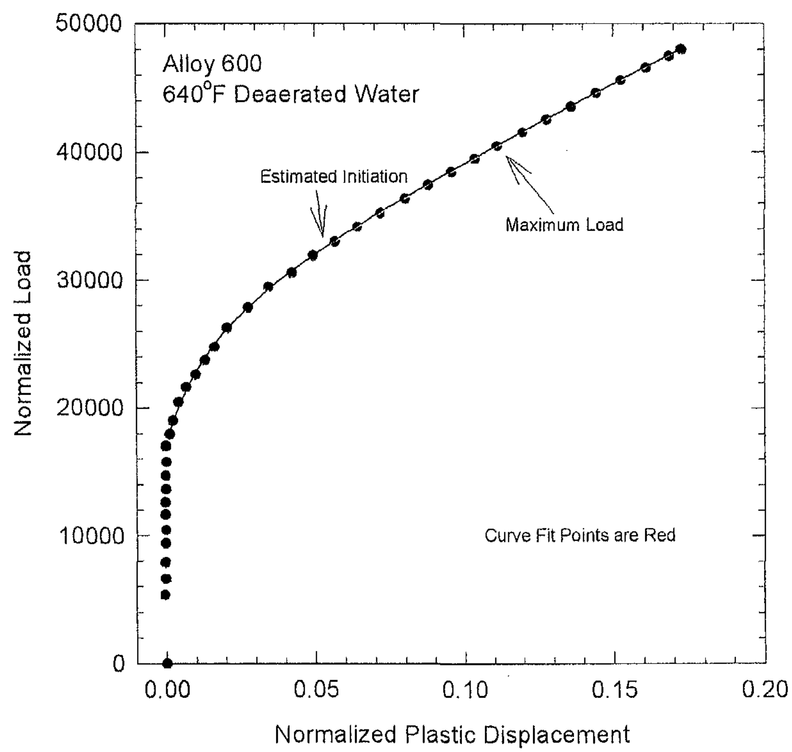
Procedure (cont.)

- Establish initiation point and Normalization fit



Procedure (cont.)

- Crack length correct data beyond initiation



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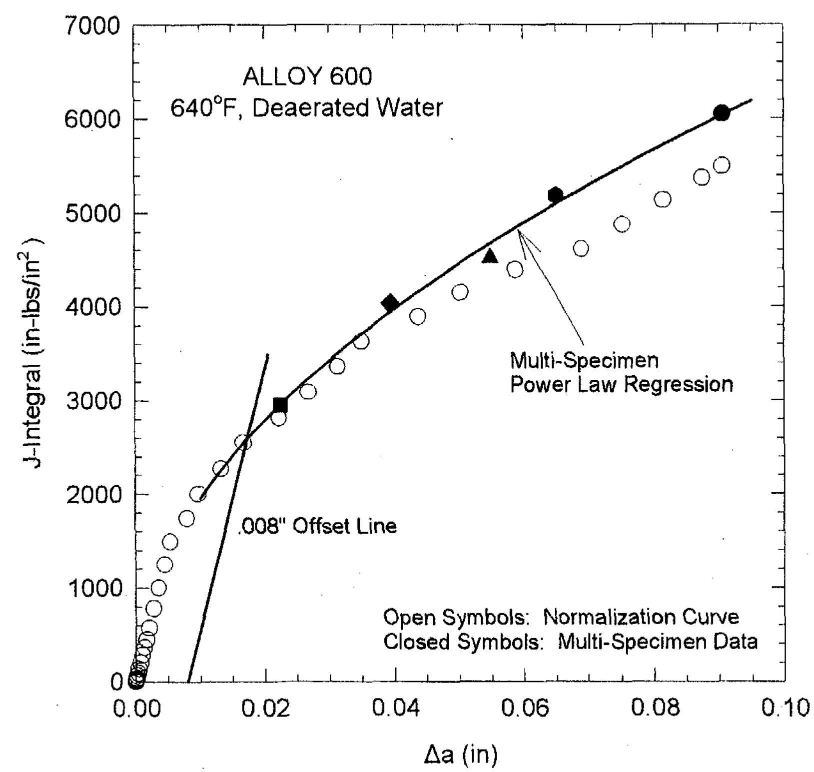
Procedure (cont.)

- Generate R-curve from load, displacement and crack length data

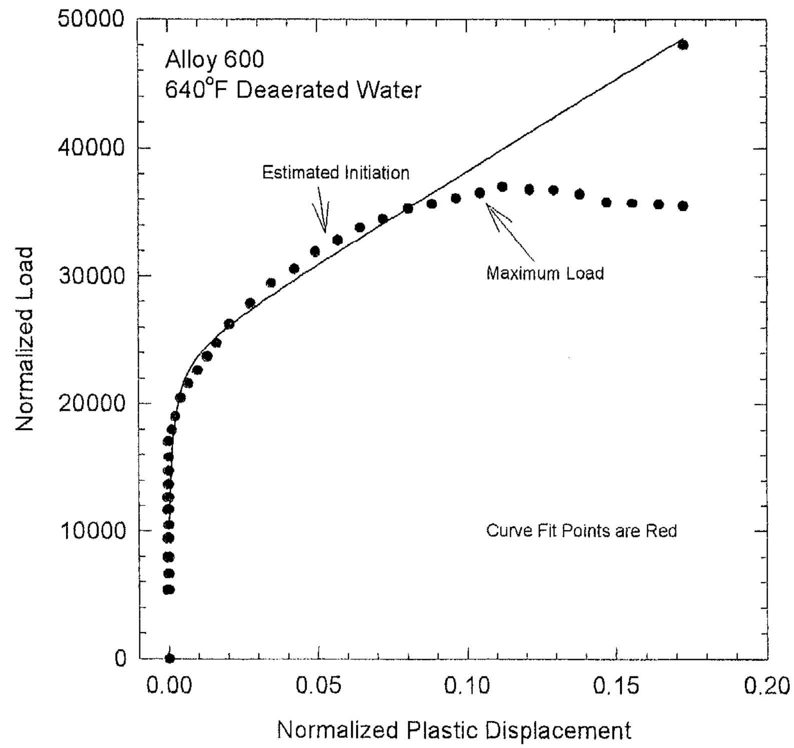


Lessons Learned

- Fitting data below normalized displacement of 10^{-3} can cause poor fit to data near J_{IC}
  - overestimate J_{IC} / predict negative crack extensions
- Estimating initiation to be max load usually wrong and can result in fits that give inaccurate results
- "Wavy" or discontinuous load-displacement curves can make normalization technique difficult and leads to inaccuracies
  - e.g. from "dynamic strain aging" effects, ringing, or poor instrumentation
  - however, "pop-ins" can be properly characterized

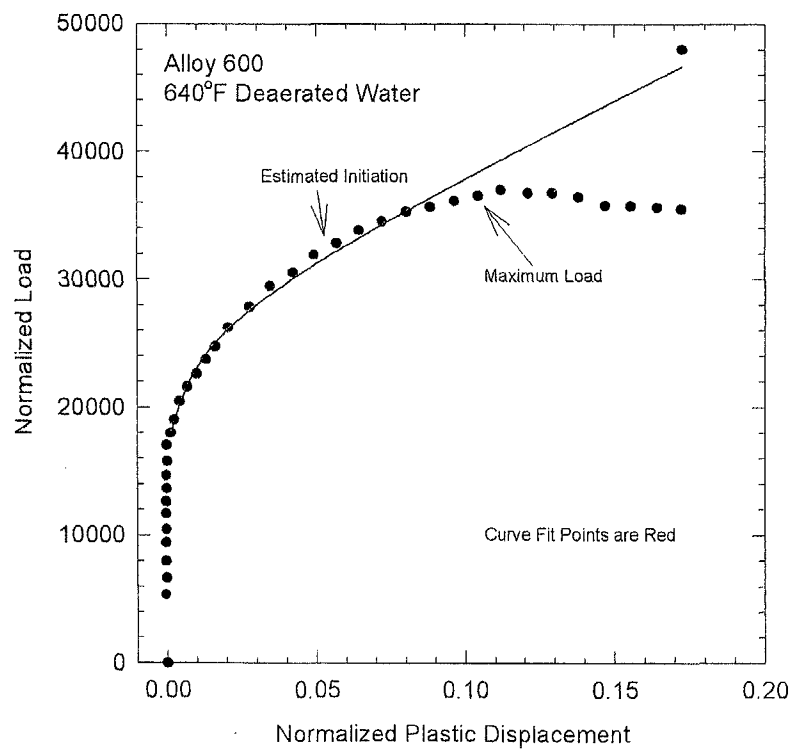
Lessons Learned (cont.)

- Fitting data below normalized plastic displ. of 10^{-3}



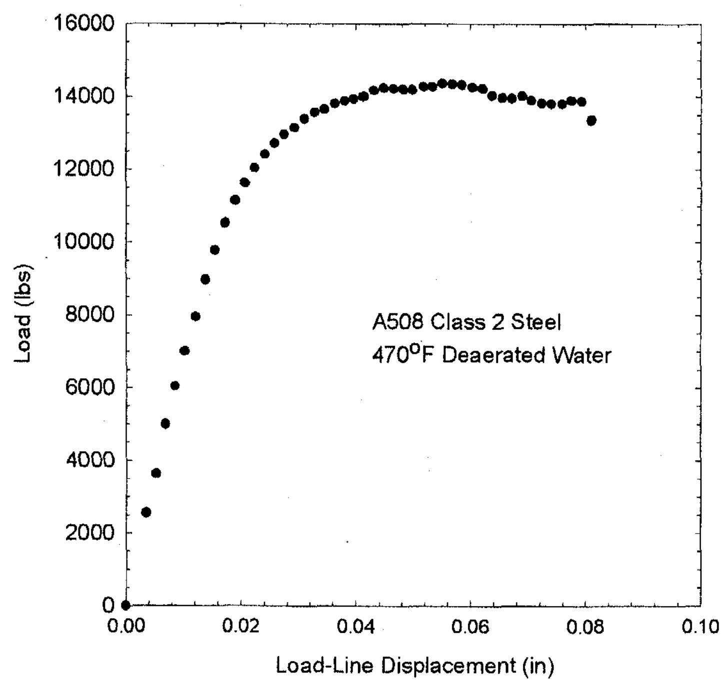
Lessons Learned (cont.)

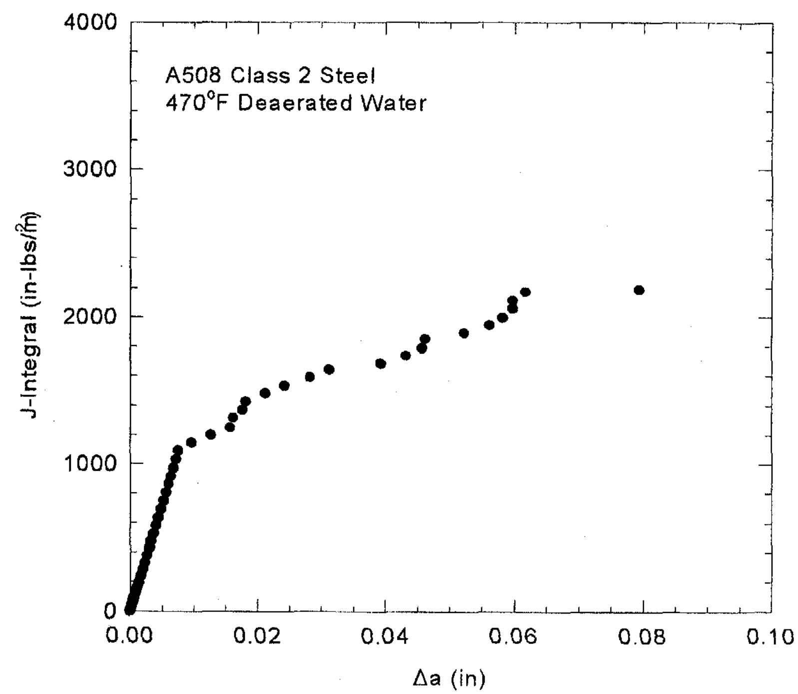
- Fitting data to just below max. load



Lessons Learned (cont.)

- Wavy load-displacement curve = wavy R-curve



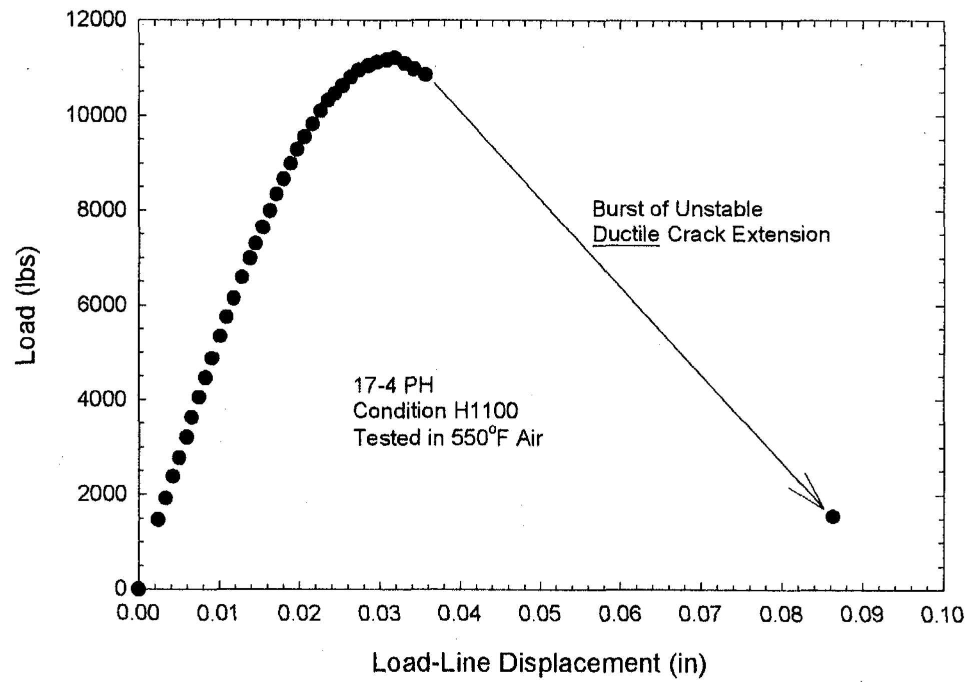


Lessons Learned (cont.)

- Excessive bursts of cracking such that the final crack length is >> the initial crack length consistantly yields inaccurate (high J_{IC}) results
  - limit maximum crack extension and require stable extension

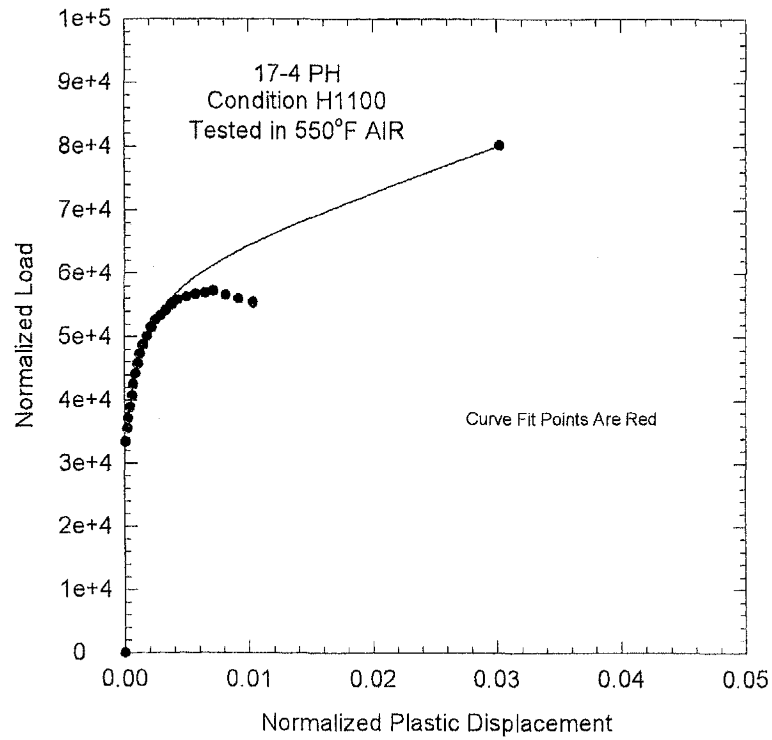
Lessons Learned (cont.)

- Excessive crack extension



Lessons Learned (cont.)

- Excessive crack extension



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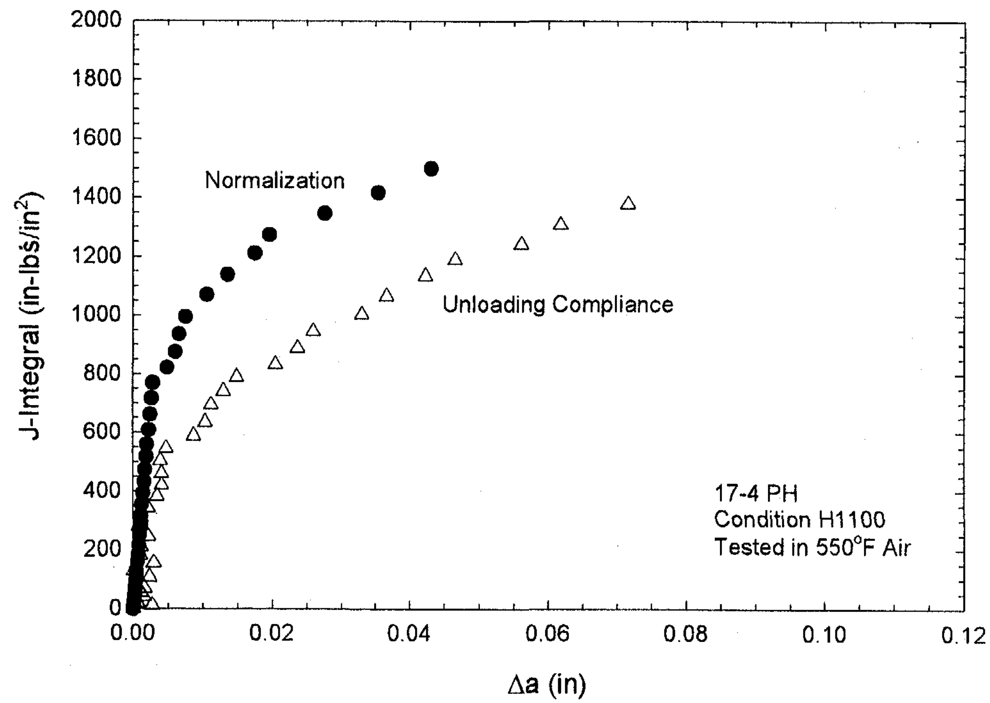
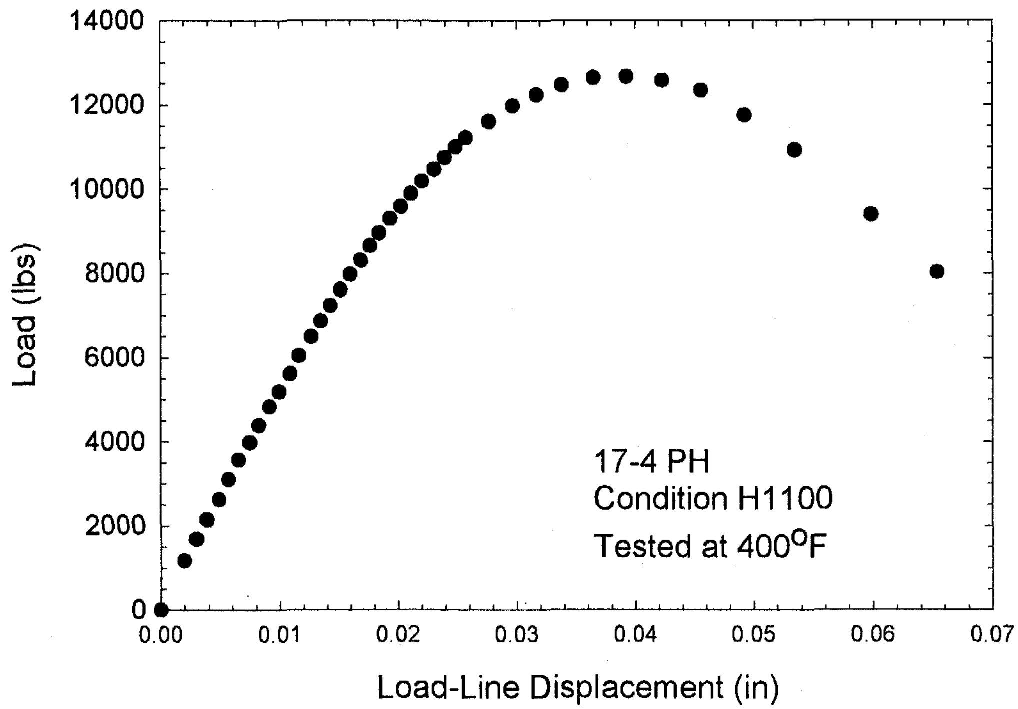
Lessons Learned (cont.)

- Excessive crack extension



Lessons Learned (cont.)

- Limit crack extension



Lessons Learned (cont.)

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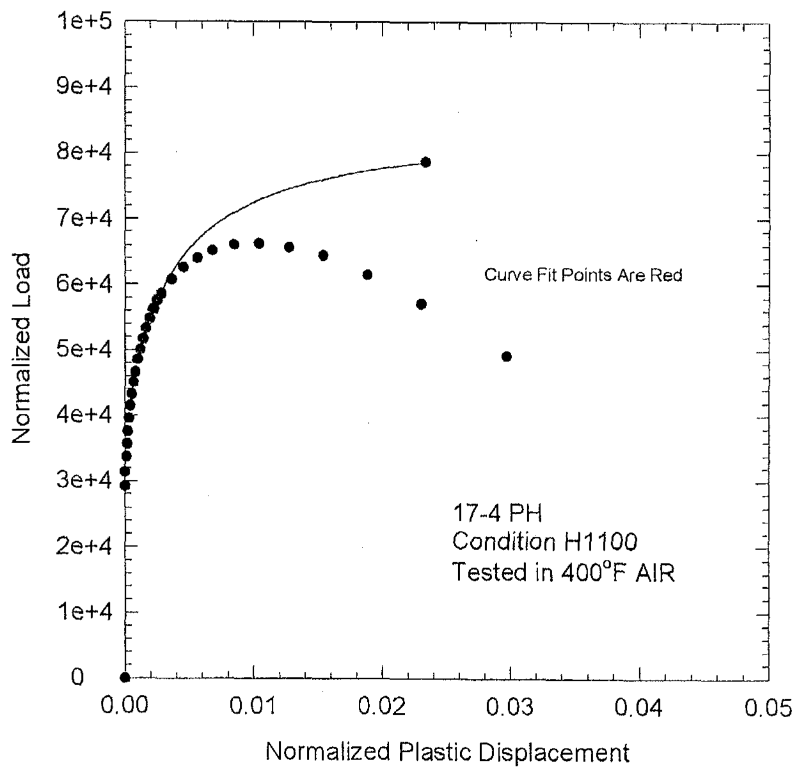
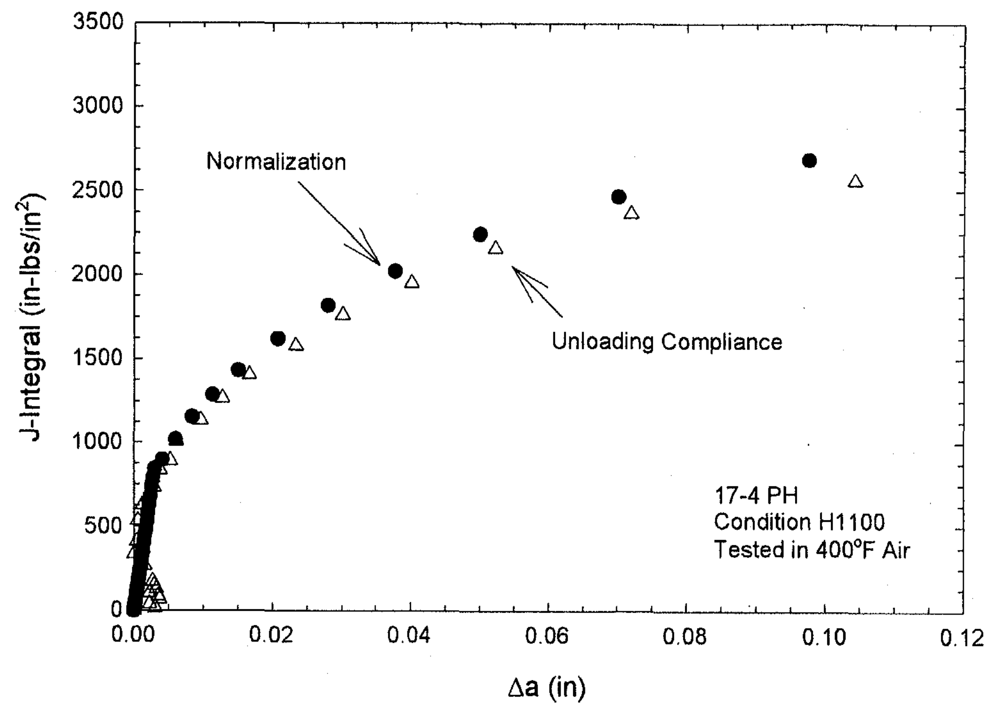


Lessons Learned (cont.)

- Limit crack extension



Conclusions

- The normalization technique for single specimen R-curve and J_{IC} determination can be very effective.
- Much like EPD, this technique requires some user interpretation/judgement during data analysis and may be difficult to standardize or fully automate even with strict analysis rules.

APPENDIX

J-R Curve Normalization Technique

This appendix summarizes the normalization method used to determine J-R curves and J_{IC} values from experimental load versus load-line displacement records as long as the initial and final crack lengths are known. The normalization process involves an initial analysis of the data to establish an appropriate normalized load-displacement function for a given data set. An iterative process is then used to determine the amount of crack extension at each data point based on the normalization function. The detailed analysis procedures for each of these steps is provided below.

Initial Analysis to Establish Normalization Function

The analysis begins by normalizing each load-displacement data pair. The load is normalized using the following equation:

$$P_{Ni} = \frac{P_i}{WB[\frac{W-a_{bi}}{W}]^{\eta_{pl}}} \qquad [A1]$$

where P_{Ni} is normalized load, P_i is instantaneous load at the i^{th} data point, W is specimen width, and B is specimen thickness (i.e., minimum thickness for side grooved specimens). The value of η_{pl} is given by

$$\eta_{pl} = 2 + 0.522\,(\frac{W-a_{bi}}{W}) \qquad [A2]$$

where a_{bi} is the instantaneous blunting-corrected crack length. In the current analysis, calculation of a_{bi} differs slightly from that recommended by the proposed ASTM method. Within the crack blunting regime (i.e., for J_i values up to a critical value, $J_{bl,}$ corresponding to the transition from crack blunting to tearing), the amount of blunting (Δa_{bi}) is proportional to the applied J_i value, so a_{bi} is given by

$$a_{bi} = a_o + \frac{J_i}{2\,m\,\sigma_f} \qquad [A3]$$

where a_0 is the initial crack length, σ_f is the flow strength (i.e., average of yield and ultimate strength levels) and m is the constraint factor (m=1 for materials with low strain hardening capabilities, such as Alloy X-750, 17-4PH and steels; m=2 for materials with high strain hardening capabilities, such as Type 316 stainless steel and Alloy 600). This is consistent with the ASTM procedure. In contrast with ASTM methodology, however, the blunting portion of the crack length does not increase in the crack tearing regime (i.e., for J_i values above J_{bl}). Therefore, in the current analysis the blunting-corrected crack length at J_i levels above J_{bl} is assumed to be constant and is given by

$$a_{bi} = a_o + \frac{J_{bl}}{2\,m\,\sigma_f} \qquad \text{[A4]}$$

J_{bl} is the value of J where the J-R curve begins to deviate from the blunting line, and it must be determined by an iterative process. A simple method for estimating J_{bl} during normalization data reduction is provided later. The initial value of J_i and J_{bl} used in Equations [A3] and [A4] are calculated for crack length a_o using the following equation:

$$J_i = \frac{K_i^2\,(1-v^2)}{E} + J_{pli} \qquad \text{[A5]}$$

where K_i is the stress intensity factor and J_{pli} is the plastic component of J as defined in ASTM E1820-96.

Each corresponding load-line displacement value (v_i) is then normalized to give a normalized plastic displacement (v'_{pli}):

$$v'_{pli} = \frac{v_{pli}}{W} = \frac{(v_i - P_i\,C_i)}{W} \qquad \text{[A6]}$$

where C_i is the elastic compliance of the specimen with crack length a_{bi} and v_{pli} is the plastic load-line displacement. The final load-displacement data pair is then normalized using Equations [A1] and [A6] except that the final measured crack length is used to compute P_{Ni} and v'_{pli}.

The normalized load-displacement data pairs within the blunting regime and the final normalized data pair are fit with the following analytical normalization function:

$$P_N = \frac{q + r\,v'_{pl} + s\,(v'_{pl})^2}{t + v'_{pl}} \qquad \text{[A7]}$$

where q, r, s, and t are fitting coefficients. When data points prior to maximum load or at very small v'_{pli} values ($<10^{-3}$) do not conform to the normalization function, they are deleted and the function is refit. The end of the blunting region can be estimated by constructing a straight line tangent from the final normalized data point to the knee of the data plot. The fitting procedure is repeated until the normalization function predicts the final P_N value within 0.5% and provides an adequate fit of the remaining data pairs, especially for the data just prior to the point of tangency. It is noted that the J_i value at the point of tangency provides a reasonable estimate of J_{bl}. Normalized data pairs consistently falling above the resulting normalized function are indicative of an inadequate fit.

Iterative Analysis to Determine Amount of Crack Extension

An iterative process is next used to force all other normalized load-displacement data pairs within the tearing regime to lie on the fitted curve. This involves adjusting the crack length of each data set and using the adjusted crack length to recalculate P_{Ni} and v_{pli}' (i.e., substituting a_i for a_o in the Equations [A1] through [A6]) until the normalized load-displacement point falls on the function defined by Equation [A7].

The estimated blunting-corrected crack lengths together with the corresponding load and load-line displacement values are then used to compute J as a function of crack extension (Δa). J_{IC} can then be determined for this J-R curve using the conventional methods outlined in ASTM E1820.