DETERMINATION OF LOCAL APPROACH PARAMETERS ON THE BASIS OF THE 'EUROCURVE' FRACTURE TOUGHNESS ROUND-ROBIN RESULTS

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Abstract

The 'Euro Curve' project had an ambitious goal of producing a very large experimental dataset depicting cleavage fracture in the ductile to brittle transition region. Several laboratories participated by performing fracture mechanics tests on a nuclear grade pressure vessel forging 22NiMoCr37 (A508 Cl.2), leading to a dataset containing 757 qualified fracture toughness results using primarily compact tension (C(T)) specimen geometry. The dataset was assessed using several means to derive material characterization methods for the ductile to brittle transition region, one of these methods being the Master curve method, as standardized in ASTM E1921. In the current work, Master curve analyses of experimental results relevant to numerical analyses are reviewed. These contain the reference temperature analyses and determination of normalization fracture toughness of the Master curve scatter expression. On the basis of the experimental results, 3D elastic-plastic and finite deformation finite element analyses are carried out at respective test temperatures. Local approach analyses for cleavage initiation are performed using the Beremin model. Maximum likelihood analyses are carried out in order to evaluate the parameters of the local approach model. Two parameter inference concepts are applied, one based on the actual experimental fracture toughness results and another using the determined fracture toughness distribution via stochastic sampling. The results indicate that for typical fracture mechanics test data sample sizes local approach parameter calibration on the basis of Master curve expressed fracture toughness distribution rather than the actual results is the most reliable method.

Introduction

The use of fracture mechanics in design and failure assessment is in some practices impeded by the difficulties in quantifying the structure related constraint and transferability properties of experimental test data. It is well known that specimen size, crack depth and loading conditions may affect the material's fracture toughness. Several methods have been developed to accurately predict the dependency of fracture toughness on constraint and several parameters have been derived for this characterization, one general family focusing on fracture micromechanical aspects has been termed as "local approach" methods. Experimentally transferability of small specimen toughness data to real structures has long been the key issue in fracture mechanics research. Methods based on the Weibull statistic, such as the "Master curve" methodology along with the local approach methods of fracture, have been developed and are able to characterize the scatter of fracture toughness test results and the effects of specimen dimensions on the data distribution, making it possible to define fracture toughness parameters for a given probability of failure, and develop scaling models for toughness transferability.

For cleavage fracture, the most successful single model has been the Beremin model, [1, 2], applied also within the context of current work. These models have been successful in predicting failure behavior of fracture mechanics test specimens, and in some instances, behavior of structures with complex crack shapes and loading conditions. The overall problems lie in the requisites set to intrinsic parameters of the local approach models, their quality and unavoidable dependencies to several variables of the fracture mechanical problem. As such, the development of these models has focused on demonstrating the unambiquity of these parameters and methods applicable for their determination.

The Master curve method was successfully applied in [3, 4] to assess the Eurocurve fracture toughness dataset. The results of these studies are utilized in the current work to investigate the behavior of the Beremin model in the ductile to brittle transition region. Two calibration approaches are utilized, one based directly on the fracture toughness data sample and other on the Master curve fracture toughness scatter distribution. The current work exploits the exceptionally large fracture toughness dataset in a continuing effort to develop local approach models for cleavage initiation as well as to improve uniqueness properties of parameter inference methods.

Testing and Material

Detailed information regarding the fracture toughness testing, material and analysis methods can be found from [3, 4]. The compact tension (C(T)) specimens were extracted from a single segment of a large nuclear grade pressure vessel forging 22NiMoCr37 (A508 Cl.2). Crack fronts were located from $1/4 \cdot t$ to $1/2 \cdot t$ to a material segment demonstrated to be homogeneous by preliminary investigations. The fracture toughness tests were performed on standard geometry C(T) specimens having thicknesses 12.5 mm, 25 mm, 50 mm, and 100 mm. The initial crack depth to specimen width, a/W, ratio was close to 0.6 for all specimens. The tests were performed in accordance with ESIS P2 procedure [5], whilst specimen prefatigue was conducted in accordance with ASTM E1921 [6]. The specimen data used in current study is extracted from non-side grooved specimen results. Yield strength temperature dependency was interpolated from tensile test results using a curve it:

$$\sigma_0 = 450 + 1294 \cdot Exp\left[-0.0147 \cdot \left(T + 273.15\right)\right], \tag{1}$$

where T is the temperature in °C. Since no direct information concerning strain hardening was available in the finite element analyses (FEA) a correlation [7]

$$\left(\sigma_0 / \sigma_{ts} = \left(30 \cdot 1/N\right)^{-1/N}\right), \tag{2}$$

was applied, where σ_{ts} is the ultimate tensile strength and N is the strain hardening coefficient in a Ramberg-Osgood type of a true stress-strain curve representation.

Master Curve Analysis

The Master Curve analysis followed the standard ASTM E1921-2002 [6]. For the comparison of different size specimen data, and for the calculation of the Master Curve transition temperature T_0, all data were thickness-adjusted to the reference flaw length (thickness) B_0 = 25 mm as prescribed in E1921-2002:

$$K_{25mm} = K_{\min} + (K_{JC} - K_{\min}) \cdot \left(\frac{B}{B_0}\right)^{1/4}, \tag{3}$$

where $K_{\min}$ is the minimum fracture toughness, B_0 the reference thickness of $25\ mm$, B the thickness of the fracture toughness value, K_{JC}, to be adjusted to the reference fracture toughness value, K_{25mm}.

For all data sets, the reference temperature, T_0, was estimated using a multi-temperature randomly censored maximum likelihood expression

$$\sum_{i=1}^{n} \frac{\delta_i \cdot \exp\{0.019[T_i - T_0]\}}{11 + 77 \cdot \exp\{0.019[T_i - T_0]\}} - \sum_{i=1}^{n} \frac{(K_{IC_i} - 20)^4 \cdot \exp\{0.019[T_i - T_0]\}}{(11 + 77 \cdot \exp\{0.019[T_i - T_0]\})^5} = 0, \tag{4}$$

where n is the sample size and δ_i a censoring parameter, having a value of 1 for a cleavage initiation event and 0 for data meeting the censoring criteria in [6].

In the local approach calibration the scatter of the Master curve was utilized when stochastically generating datapoints. According to [6] the failure probability can be given as

$$P_f = 1 - \exp\left(-\left(\frac{K_{Jc} - K_{\min}}{K_0 - K_{\min}}\right)^4\right), \tag{5}$$

where K_0 is the normalization fracture toughness corresponding to a 63.2% failure probability. K_0 was estimated according to expression

$$K_0 = \left(\frac{\sum_{i=1}^{n} (K_i - K_{\min})^4}{\sum_{i=1}^{n} \delta_i - 1 + \ln 2}\right)^{1/4} + K_{\min} \tag{6}$$

and its temperature dependency evaluated according to the Master curve equation

$$K_0 = 31 + 77 \cdot Exp\left[0.019 \cdot (T - T_0)\right]. \tag{7}$$

Finite element and local approach analyses

Numerical analyses at temperatures corresponding to experimental fracture toughness data were carried out using the WARP3D research code version 13.9 developed at University of Illinois [8]. The computations were carried out with quarter specimen 3D models using isotropic incremental plasticity theory and finite strain deformations. The deformation description was presented in a finite strain Lagrangian framework using 20 node brick elements. The results presented in the current paper focus on 12.5 mm and 25 mm thick C(T) specimens. A mesh of a 12.5 mm thick C(T) specimen is given in Fig. 1.

On the basis of numerical and experimental fracture toughness results for the transition region the parameters of a two-parameter Weibull distribution were fitted using a maximum likelihood (MML) scheme. This was performed using an in-house Mathematica [9] written scripting interface routine. The Beremin model for cleavage initiation is presented as in [2]

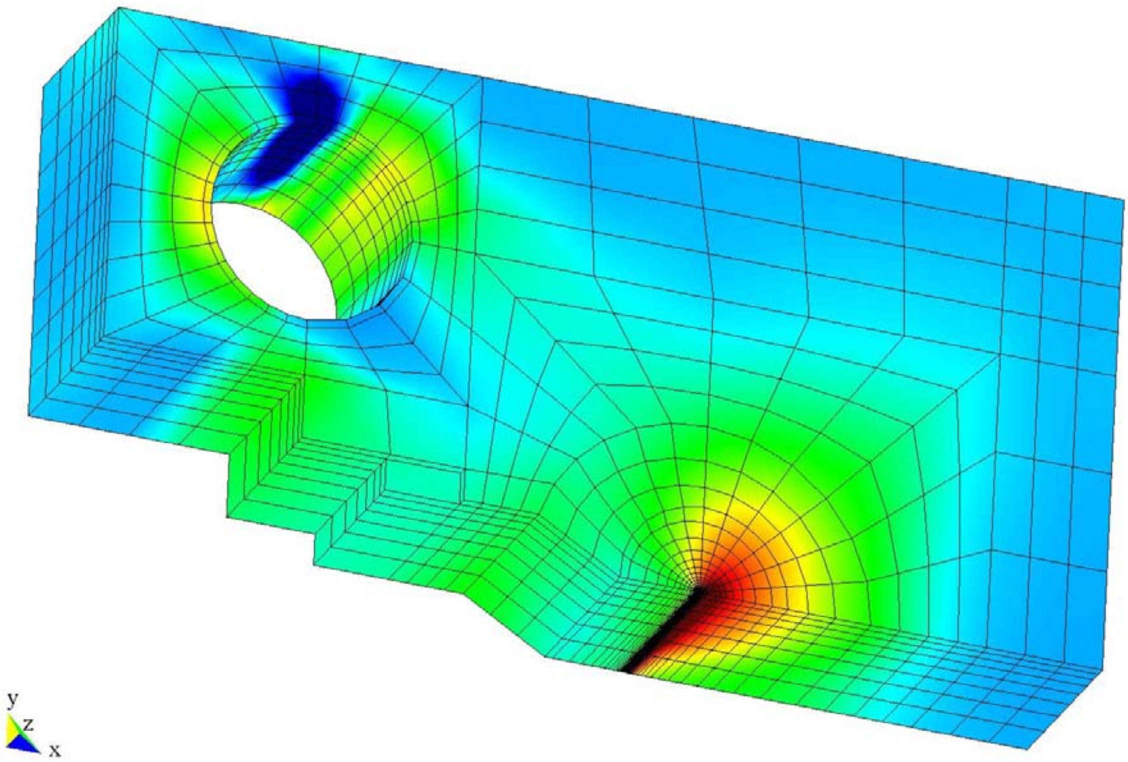

FIGURE 1. FEA C(T) specimen mesh.

$$P_f = 1 - \exp\left[-\left(\frac{\sigma_w - \sigma_{th}}{\sigma_u - \sigma_{th}} \right)^m \right], \tag{8}$$

where σ_w is the Weibull stress, σ_u the scale parameter, m the shape parameter and σ_{th} the threshold stress, set in current work to have a constant null value. The Weibull stress is presented as

$$\sigma_{\mathrm{w}} = \left\{ \frac{1}{\mathrm{V}_0} \int_{\Omega} {\sigma_1}^m d\Omega \right\}^{\frac{1}{m}}, \tag{9}$$

where σ_1 is the first principal stress, V_0 is a reference volume set to unity and Ω is the fracture process zone. The process zone was defined as $\Omega : \sigma_1 \geq \sigma_0$. The form of the used MML equation for a Weibull probability density function was

$$L(m, \sigma_u) = \left(m\sigma_u^{-m} \right)^r \prod_{i=1}^{r} \sigma_{wi}^{m-1} \exp\left[-\sigma_u^{-m} \sum_{i=1}^{r} \sigma_{wi}^m \right] \exp\left[-(n-r)\sigma_u^{-m}\sigma_{wc}^m \right], \tag{10}$$

here $n-r$ is the number of censored samples, censoring being carried out for fracture toughness according to the criteria given in [6].

Two different philosophies were adopted for the calibration process. First, a direct approach by using the actual experimental samples at a fixed temperature was utilized. Second, the Master Curve normalization toughness was determined and the resulting distribution was used to stochastically generate the sample for parameter inference. In the latter case, latin hypercube sampling [10] was used as the stochastic routine. Sample fracture toughness i is generated according to equation:

$$K_0^i = K_{\min} + \left(K_0 - K_{\min}\right)\left[-LN\left(1-\frac{1}{m}\left\{P_f^i+\left(i-1\right)\right\}\right)\right]^{\frac{1}{4}}, \qquad (11)$$

where m is the number of samples (500) and P_f^i is the local failure probability for sample i.

Master Curve Analysis Results

The Master curve analysis results for 12.5 mm and 25 mm thick C(T) specimens are presented in Fig. 2. The normalization fracture toughness was determined temperature dependently and the temperature dependency fitted following the Master curve method. Results for 12.5 mm thick C(T) specimen at two temperatures is presented in Fig. 3 and the K_0 temperature dependency used in local approach calibrations following Eq. (11) is given in Fig. 4. In the analysis of Fig. 4 the whole Eurocurve dataset with all specimen sizes was utilized. The K_0 reference temperature achieves a value of -84°C.

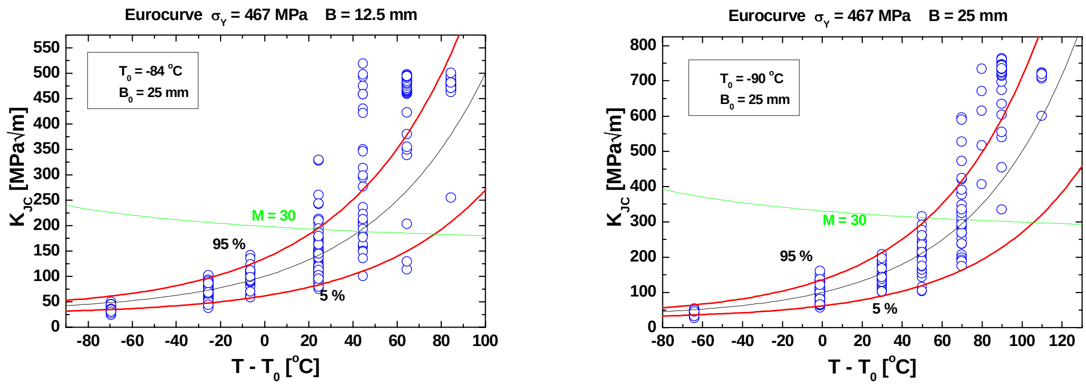

FIGURE 2. Master curve analysis results of 12.5 mm and 25 mm thick C(T) specimens.

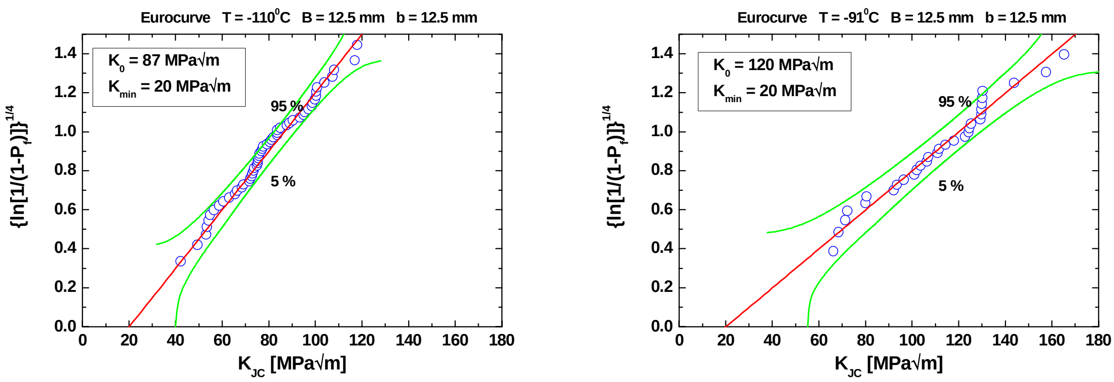

FIGURE 3. Normalization fracture toughness analysis results for 12.5 mm thick C(T) specimen at temperatures of-110°C and -91°C.

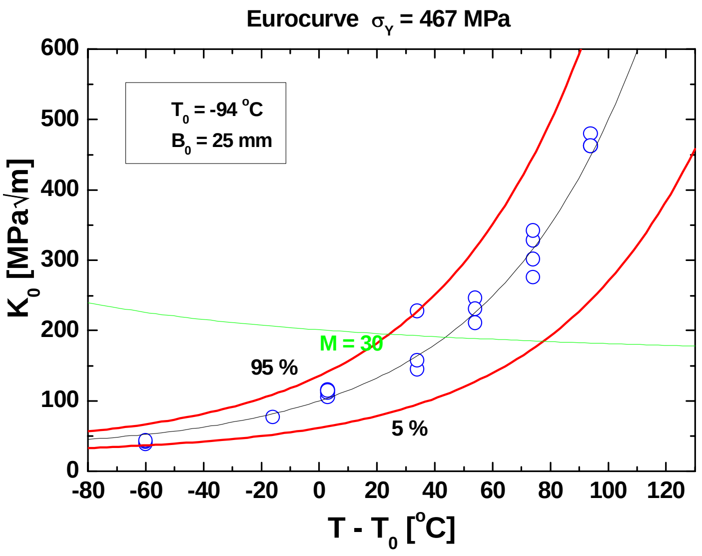

FIGURE 4. K_0 Master curve analysis results

Local Approach Analysis Results

Comparison between failure probabilities of experimental results (rank probabilities) and numerical estimates are presented in Figs. 5 and 6. The results in Figs. 5 and 6 are presented for temperatures well established within the transition region, i.e. not lower shelf nor close to upper shelf, where the performance of the Beremin model begins to deteriorate. This occurs in particular when approaching upper shelf, on lower shelf different parameter inference methods begin to produce differing results since the applied Master curve method itself is not suitable for usage within lower shelf. It is noted that for larger specimens exhibiting small-scale yielding conditions to higher values of crack driving force the Beremin model behaves better in accordance with experimental response, as can be expected.

The values of the Beremin model parameters, the shape parameter m and scale parameter σ_u, are presented in Figs. 7 and 8. The scale parameter has a clear well-defined, also relatively large, dependency on the thermal part of yield strength as well as the normalization fracture toughness. The shape parameter, however, is more dependent on specimen size along with temperature. The applied parameter calibration procedure has a great influence on

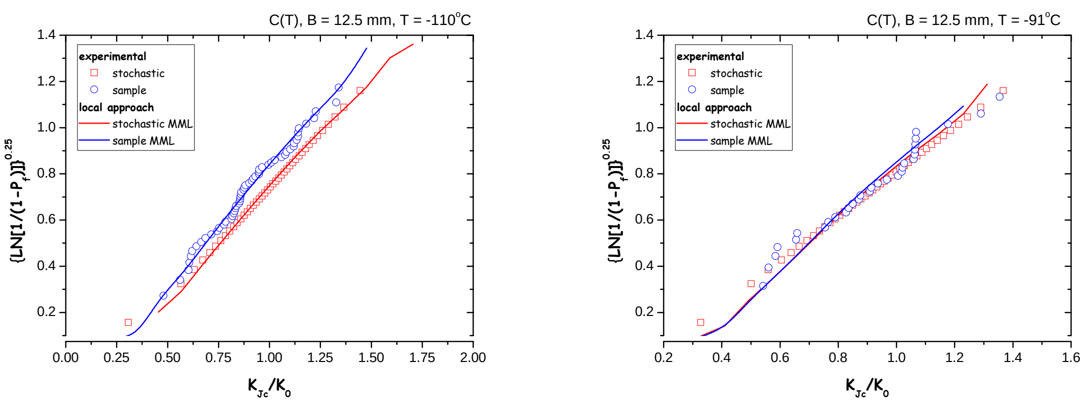

FIGURE 5. Comparison of failure probabilities between experimental and numerical results for 12.5 mm thick C(T) specimen at -110°C and -91°C for both local approach parameter estimation methods.

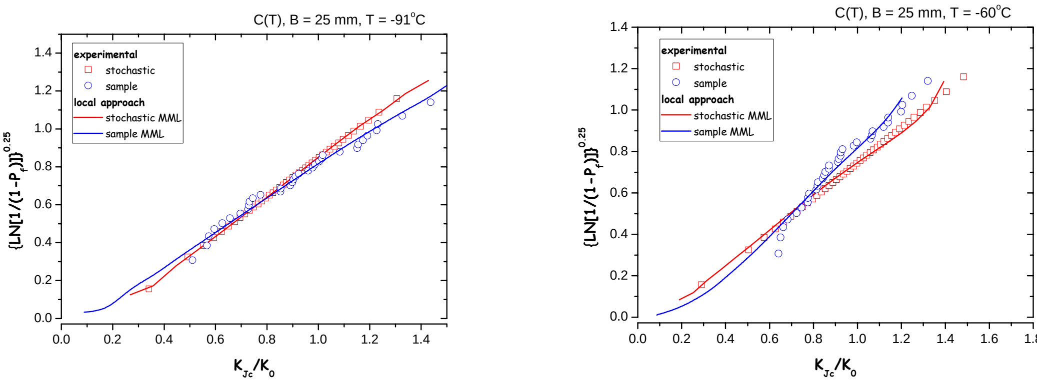

FIGURE 6. Comparison of failure probabilities between experimental and numerical results for 25 mm thick C(T) specimen at -91°C and -60°C for both local approach parameter estimation methods.

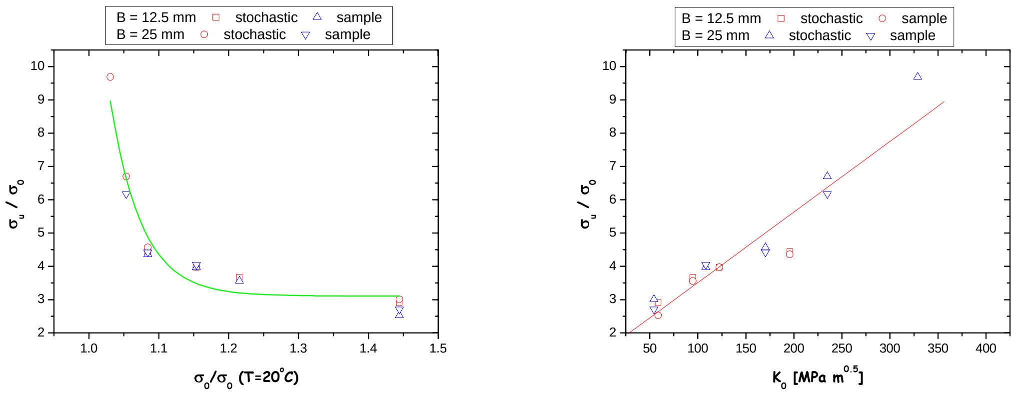

FIGURE 7. Dependency of the Beremin scale parameter on yield strength and normalization fracture toughness temperature dependency and method of analysis.

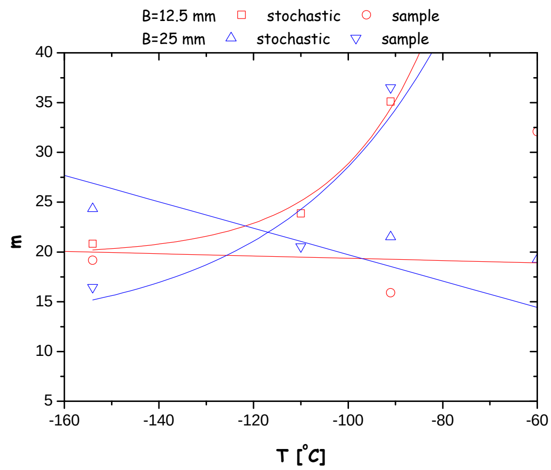

FIGURE 8. Dependency of the Beremin shape parameter on yield strength and normalization fracture toughness temperature dependency and method of analysis.

calibration results which do not lie in the transition region close to the reference temperature. The scale parameter adjust for the overall increase in fracture toughness, while the shape parameter attempts to capture the higher fracture toughness ‘rate’ (with temperature) with higher values, an effect particularly prominent in the smaller specimen size due to more pronounced overall decrease in crack tip constraint.

Summary and Conclusions

Master curve and local approach analyses of the 'Eurocurve' fracture toughness dataset specimen sizes 12.5 mm and 25 mm were carried out in order to investigate the performance of the Beremin model in the fracture toughness ductile-to-brittle transition region. The results of the work can be concluded as follows:

- The different local approach parameter inference methods produced comparable estimates within temperatures close to the Master curve reference temperature. At higher temperatures, the shape parameter becoming more dependent on temperature, specimen and fracture toughness transition region characteristics.
- The use of stochastic methods in calibration of the local approach parameters does provide a better overall description of the experimental data, as long as analyses are performed in regions where the Master curve method is applicable and satisfactory small-scale yielding conditions prevail.
- Under the conditions where the above mentioned conditions for the performance of the Beremin model are met, for small sample sizes the stochastic approach for Beremin shape and scale parameter determination is superior to using the actual fracture toughness sample, due to the data treatment benefit arising from use of the Master curve method in processing the experimental fracture toughness data.
- The temperature range at which the Beremin model can be applied with relative confidence is relatively narrow, i.e. the proximity of the reference temperature, intrinsic modifications are required to overcome this obstacle.

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