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Engineering Approaches to the Application of Fracture Toughness Data in the Nuclear Industry

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ABSTRACT

The procedures for measuring the plane strain fracture toughness, K_{Ic}, of metals were originally developed for relatively high yield strength materials, the toughnesses of which were not affected by strain rate. The application of these procedures to lower yield strength and higher toughness structural and pressure vessel steels have since revealed a perplexing combination of problems involving the effects of geometry, stable crack growth and strain rate on the measured values of toughness. Only the geometric problems were encountered in the development of the procedures for measuring K_{Ic}. For fracture in the linear elastic range of the load-displacement curve, these problems were overcome by specifying specimen dimensions sufficiently large with respect to the plastic zone size at fracture. However, in the case of structural and pressure vessel steels, it is not always possible to test specimens large enough for fracture to occur prior to general yielding. Therefore, in these cases, the effects of large-scale yielding prior to fracture cannot be avoided, but since they presently have no analytical explanation they are being treated empirically.

The empirical treatments of size effects on fracture toughness are of two types, statistical and phenomenological. The statistical treatments are based on the assumed existence of small-scale inhomogeneities that control the initiation of cleavage fracture. The resulting parameters are not necessarily independent of temperature, and for accuracy the procedures may require more than the available number of specimens. The phenomenological approaches are based on the knowledge that yielding precedes the occurrence of cleavage microcracks and that the tensile ductility increases with decreasing hydrostatic stress. In addition, it is assumed that the hydrostatic stress decreases as the crack-tip plastic zone size increases with respect to the distance to a free surface.

Early observations of size effects were made with center-cracked and edge-cracked plates, center notched spin discs, notched beams and circumferentially notched round bars. Using circumferentially notched round bar data

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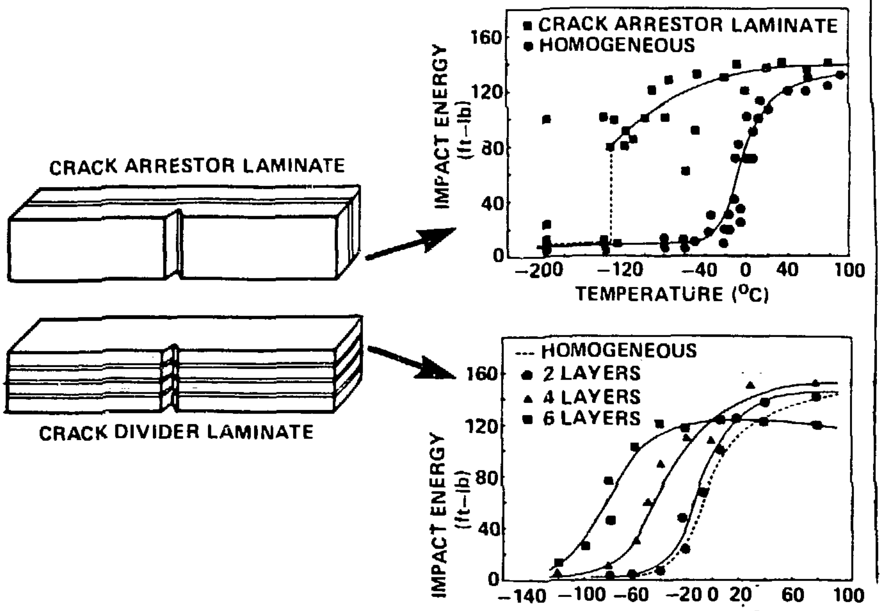
to estimate K_{Ic}, Irwin developed an empirical equation based on the parameter β_{Ic} to estimate size effects in planar specimen data. However, the notched round specimen was not adopted for general use because of problems concerning precracking, eccentricity, machine load capacity and analysis. Planar specimens loaded primarily in bending were found most practical, and size effects were avoided, at least for high yield strength low-toughness materials, by applying conservative specimen size requirements.

Recent applications of the Irwin β_{Ic} equation to small specimen fracture toughness data in the plastic range have shown that when using the onset of unstable cleavage as the measurement point, the equation eliminates size effects and reduces data scatter, but only if stable crack growth does not precede cleavage. When stable crack growth occurs first, sizes effects tend to be diminished and may even be reversed, with measured large specimen toughness values exceeding small specimen values. Because even a small amount of crack-tip forward motion generates high crack-tip strain rates, stable crack growth in a strain rate sensitive material can reduce the measured fracture toughness values, thus producing an effect opposite to that of specimen size alone. An analysis of combined strain rate and size effects indicates this possibility.

Two physical quantities that exert a controlling influence on the state of stress near a crack tip are the strain at the blunted crack tip normal to the plane of the crack and the strain in the perpendicular direction tangent to the crack front. Although it is commonly assumed that crack tips always create plane strain, this is not so, and this important fact can be demonstrated analytically for some geometries and numerically for others. Thus specimen geometry can have a significant effect on the degree of triaxial constraint that develops near a crack tip. The mode of loading can also have an effect on the near crack-tip stress state, with bending producing greater constraint than tension.

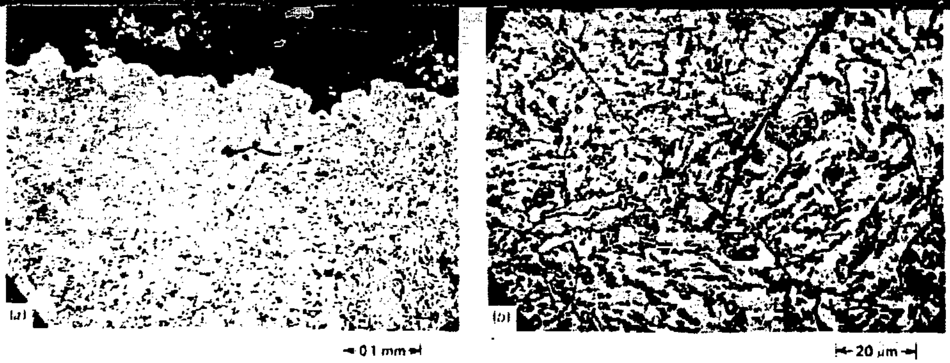
The problems of geometry and strain rate effects on toughness discussed herein are complex and difficult to solve. However, taking advantage of the improvements that have recently been made in the hardware and software available for performing three-dimensional elastic-plastic and viscoplastic stress analysis, it should be possible to significantly improve the analysis of small-specimen, elastic-plastic fracture toughness data.

LAMINATED SPECIMENS DEMONSTRATE THAT LOSS OF TRIAXIALITY CAUSES INCREASED TOUGHNESS

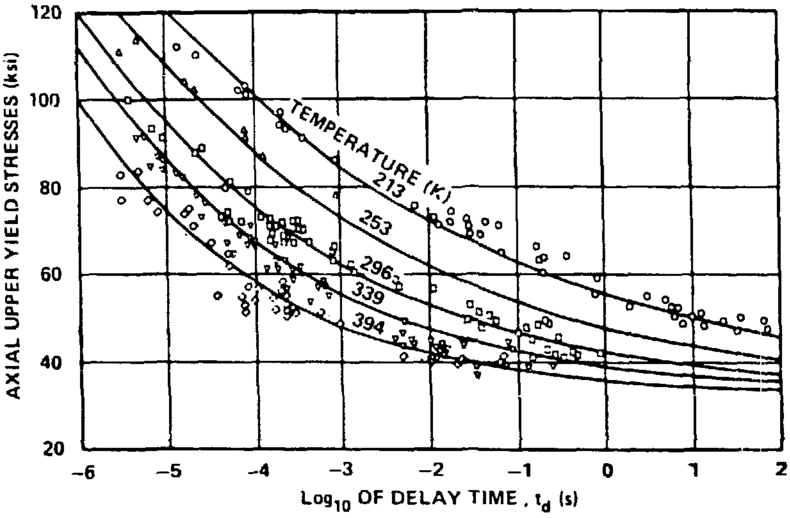


SPECIMENS BONDED WITH SILVER SOLDER

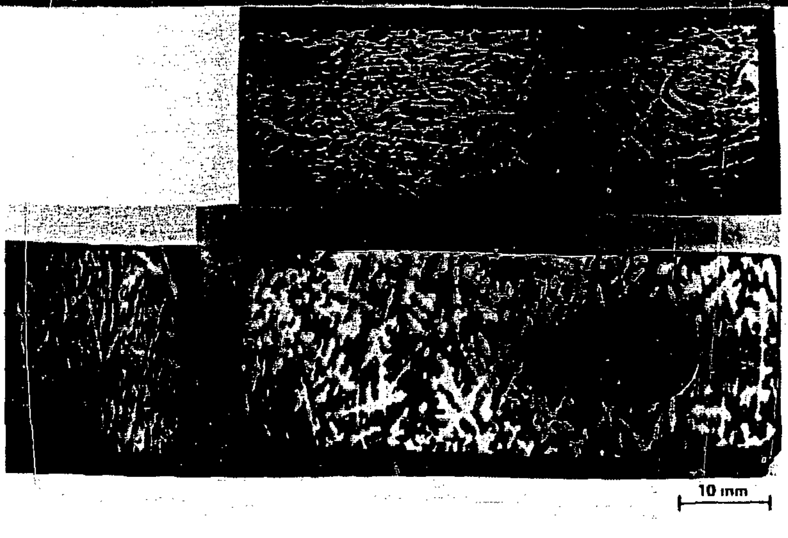
CLEAVAGE [illegible] CRACK PROPAGATION [illegible] [illegible] NEGLIGIBLE



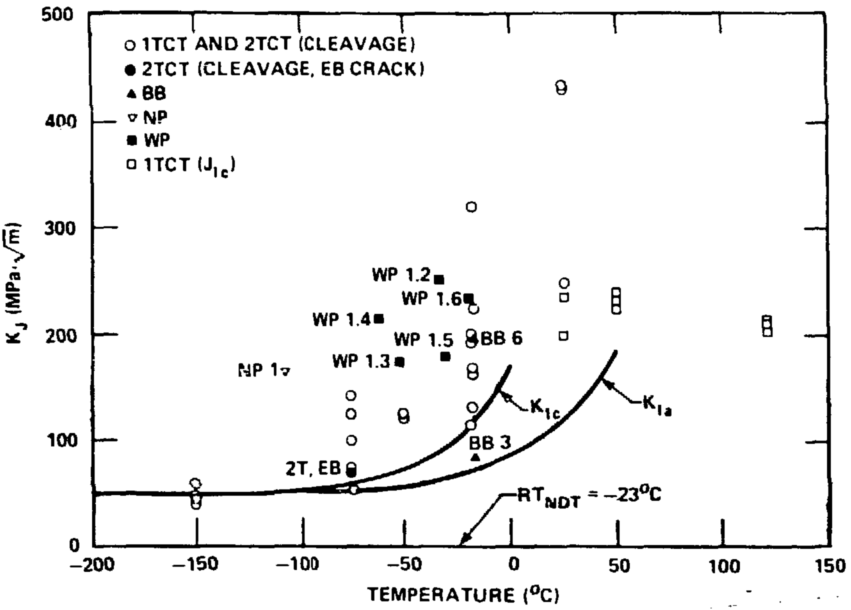
THE DELAY TIME FOR YIELDING DECREASES BY ORDERS OF MAGNITUDE WITH INCREASING TEMPERATURE



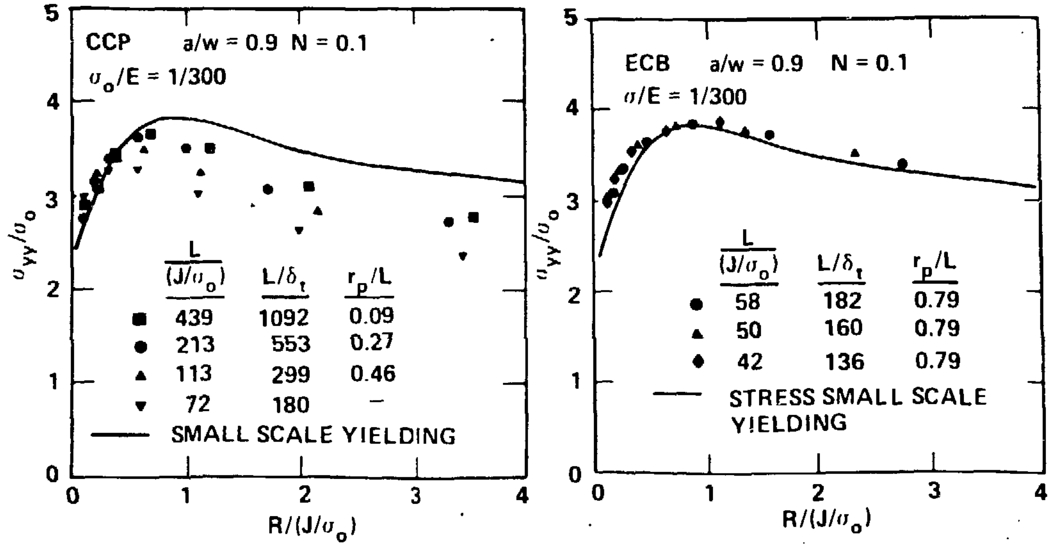
ETCHING REVEALS MACROSCOPIC REGIONS OF HIGH– AND LOW–CARBIDE-PARTICLE DENSITY IN A533 STEEL



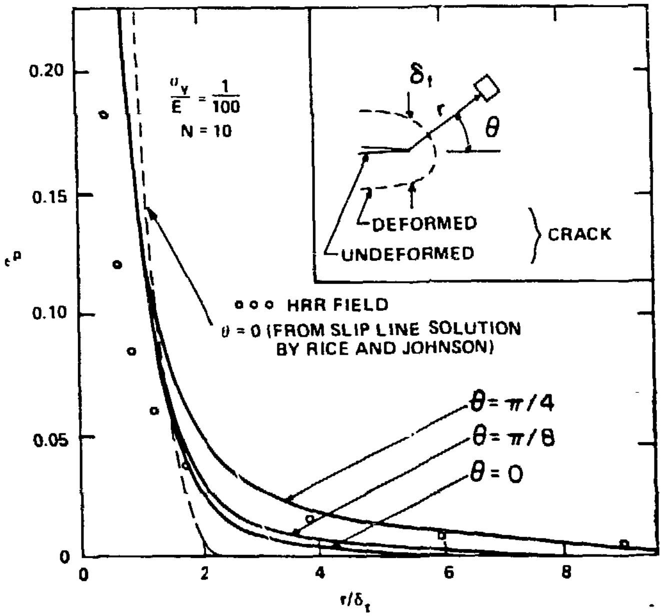
TENSILE LOADED WIDE–PLATE SPECIMENS HAVE ELEVATED INITIATION–TOUGHNESS VALUES



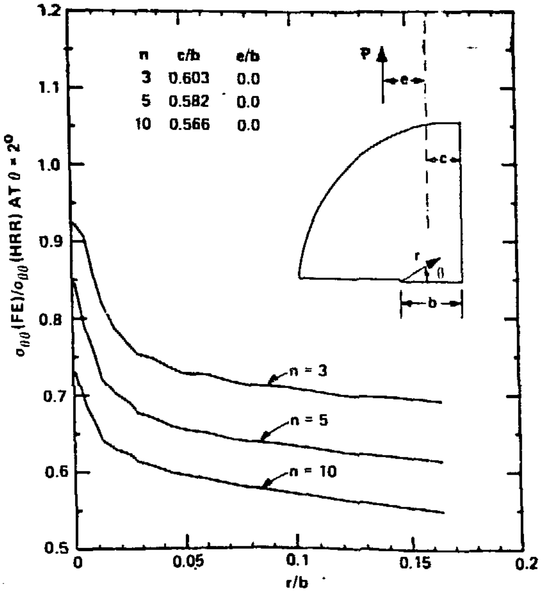
TENSILE LOADING CAUSES CRACK–TIP–STRESS MAGNITUDES AFTER YIELDING TO BECOME LESS THAN UNDER BENDING FOR THE SAME APPLIED J



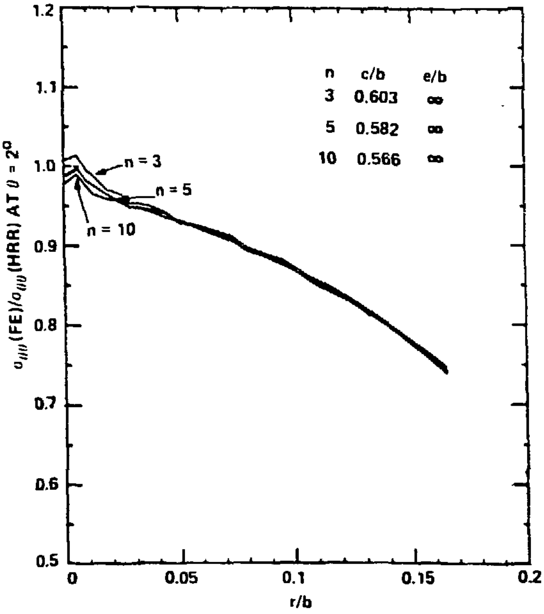
THE ANGULAR VARIATION OF PLASTIC STRAIN BECOMES NEGLIGIBLE NEAR A BLUNTED CRACK TIP



UNDER TENSILE LOADING, SMALL–SCALE–YIELDING CRACK–TIP STRESSES DECREASE WITH RESPECT TO THE HRR SOLUTION WITH DECREASING STRAIN HARDENING



UNDER BENDING LOADING, SMALL–SCALE–YIELDING CRACK–TIP STRESSES APPROACH THE HRR SOLUTION NEAR THE CRACK TIP



CRACK TIPS DO NOT NECESSARILY GENERATE PLANE STRAIN

$E\epsilon_z = \sigma_z - \nu(\sigma_x + \sigma_y)$

FOR $\epsilon_z = 0$, $\sigma_z = \nu(\sigma_x + \sigma_y)$

$$\frac{\sigma_z}{\nu(\sigma_x + \sigma_y)} = 1 \quad \text{(PLANE STRAIN)}$$

HOWEVER, THE REVERSE DOES NOT GUARANTEE PLANE STRAIN

$$\sigma_z = \nu(\sigma_x + \sigma_y) + E\epsilon_z$$

$$\frac{\sigma_z}{\nu(\sigma_x + \sigma_y)} = 1 + \frac{E\epsilon_z}{\nu(\sigma_x + \sigma_y)}$$

FOR SMALL x, $\sigma_x \sim \sigma_y \sim \frac{K_I}{\sqrt{2\pi x}}$

$$\frac{\sigma_z}{\nu(\sigma_x + \sigma_y)} = 1 + \frac{E\epsilon_z}{2\nu K_I}\sqrt{2\pi x}$$

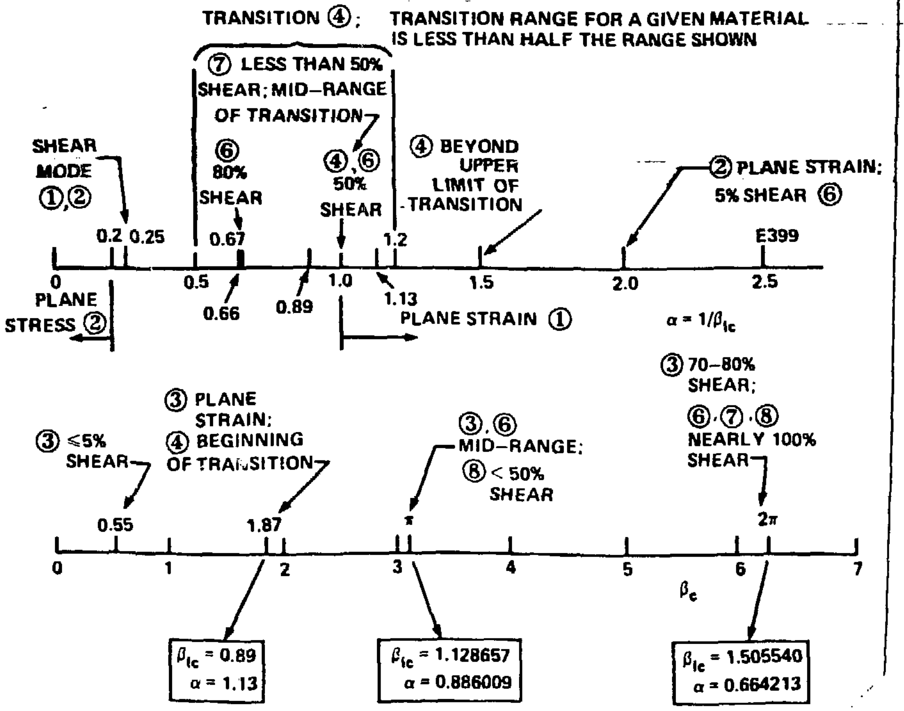
$$\lim_{x \to 0} \frac{\sigma_z}{\nu(\sigma_x + \sigma_y)} = 1 \quad \text{BUT} \quad \underline{\epsilon_z \neq 0}$$

TRANSVERSE STRAIN AT CRACK TIPS CAN BE CALCULATED FROM NUMERICAL AND ANALYTICAL RESULTS

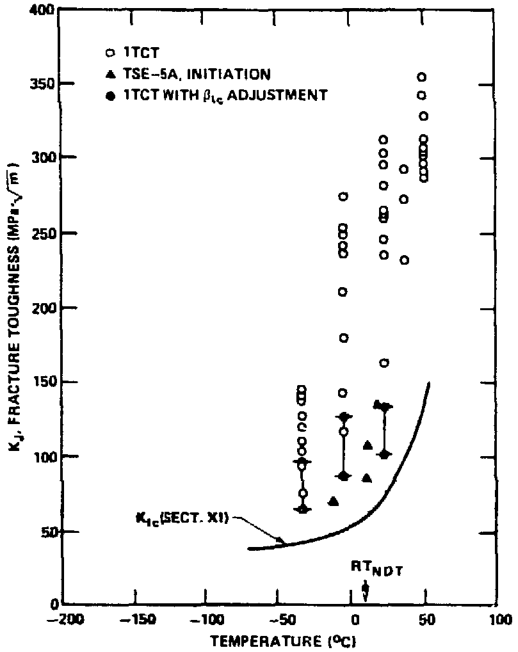
SPECIFICATION TYPE	AUTHOR	a/w	a/b	ν	ϵ_z AT $\beta_c = 0.4$
1. CRACK TIP	LEVY	–	–	0.3	$-0.18\,\epsilon_Y$
2. CT	CRUSE	0.5	1.0	0.3	$-0.17\,\epsilon_Y$
3. CT	TRACEY	0.5	1.0	0.3	$-0.22\,\epsilon_Y$
4. CCP	AYRES	0.33	2.0	0.3	$-0.11\,\epsilon_Y$
5. DECP	AMODT AND BERGAN	0.33	0.83	0.34	$-0.23\,\epsilon_Y$
6. PTC	AYRES	a/2b = 0.3	0.2	0.3	$-0.32\,\epsilon_Y$
7. BURIED CIRCULAR CRACK*	BELL; NEUBER	–	–	0.3	$-0.31\,\epsilon_Y$
8. DEEP NOTCHED ROUND*	NEUBER; SNEDDON	–	–	0.3	$+0.19\,\epsilon_Y$

(*) ANALYTICAL, CLOSED FORM

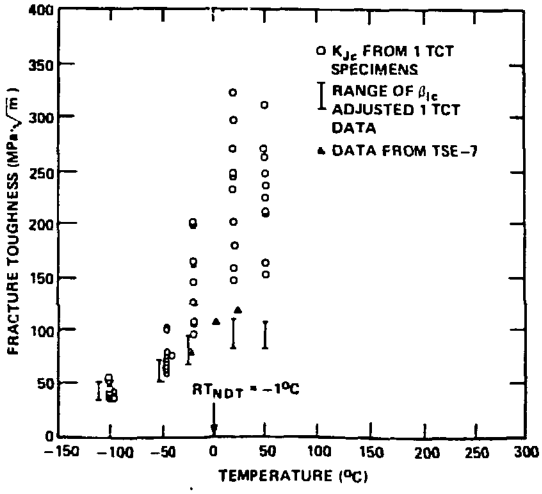
EARLY ESTIMATES OF CONSTRAINT EFFECTS WERE MADE IN TERMS OF THE PARAMETERS a AND β_c



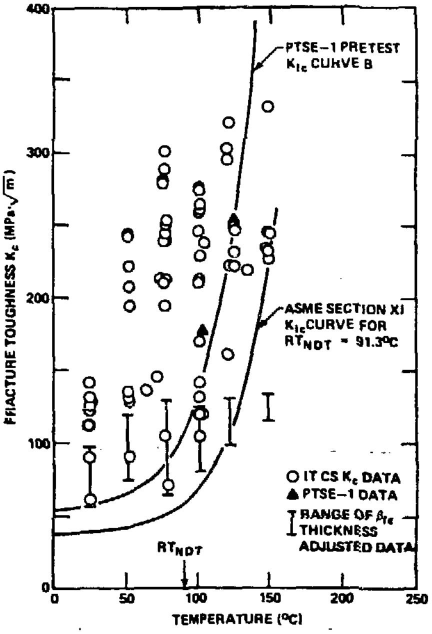
APPLYING THE β_{Ic} ADJUSTMENT FOR SIZE EFFECTS IMPROVES THE AGREEMENT BETWEEN SMALL AND LARGE SPECIMEN–TOUGHNESS VALUES



THE β_{Ic} ADJUSTMENT BEGINS TO BE OVER–CONSERVATIVE WHEN THE ADJUSTED VALUES BECOME CONSTANT



THE β_{Ic} ADJUSTMENT BEGINS TO BE OVER–CONSERVATIVE AT ABOUT THE RT_{NDT}



ELEVATED CRACK–TIP STRAIN RATES CAUSED BY STABLE CRACK GROWTH MAY REDUCE THE CLEAVAGE–INITIATION TOUGHNESS

1. ASSUME THE EXISTENCE OF A RATE–TEMPERATURE PARAMETER,

$$\lambda = T_K \log_{10}\left(\frac{A}{\dot{\epsilon}_Y}\right), \qquad \begin{cases} A = 10^8\ s^{-1} \\ \dot{\epsilon}_{Ys} = 10^{-5}\ s^{-1} \end{cases}$$

CONSTANT FOR GIVEN K_c AND THICKNESS

2. ASSUME $\sigma_{Yd} = \sigma_{Ys} + 20$ ksi

3. FOR PLANE STRAIN, ASSUMING $\nu = 0.3$, AND AT $r = r_Y$, $\epsilon^P = 0$, AND $\sigma_x = \sigma_z$

$$\sigma_Y = \sqrt{3}\,\sigma_{Yd} \text{ AND } r_Y = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_{Yd}}\right)^2$$

4. USING $\sigma_Y = \frac{K_I}{\sqrt{2\pi r}}$ AND ASSUMING $\dot{K} = 0$,

$$\dot{\sigma}_Y = \frac{3\sqrt{3}\,\pi\,\sigma_{Yd}\,\dot{a}}{\left(\frac{K_I}{\sigma_{Yd}}\right)^2}$$

5. USING HOOKE'S LAW

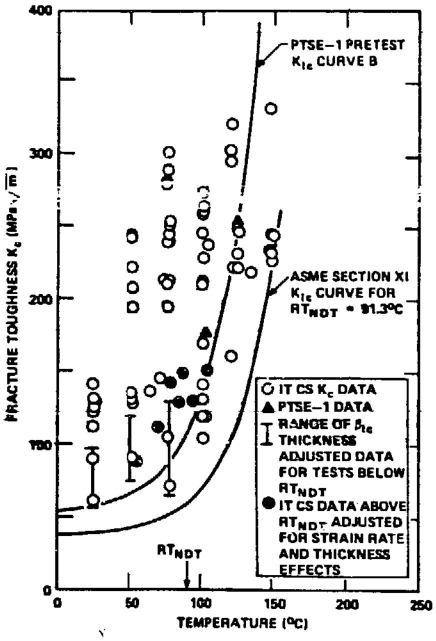
$$\dot{\epsilon}_Y = \frac{12.13\,\epsilon_{Yd}\,\dot{a}}{\left(\frac{K_I}{\sigma_{Yd}}\right)^2}$$

6. ASSUME $\dot{a} = \left(\frac{T - RT_{NDT}}{50}\right)$, mm/s

7. FROM $\lambda_{STATIC} = \lambda_{DYNAMIC}$

$$T_s = T_K\left(\frac{8 - \log_{10}\dot{\epsilon}_Y}{13}\right) - 273.15,\ ^{\circ}C$$

ADJUSTMENT FOR STRAIN RATE AS WELL AS SIZE EFFECTS IMPROVES SMALL SPECIMEN TOUGHNESS ESTIMATES WHEN STABLE CRACK GROWTH PRECEDES CLEAVAGE



DISCLAIMER