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J_{Ic} Fracture Toughness of Ferritic DCI Alloys: A Comparison of Two Versions of ASTM E 813

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J_{Ic} Fracture Toughness of Ferritic DCI Alloys: a comparison of two versions of ASTM E 813*

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Abstract

The fracture toughness of several ductile cast iron (DCI) alloys has been calculated according to two versions of the ASTM Standard covering the determination of J_{Ic}. The original version (ASTM E 813-81) had previously been used to establish the relationship between ferritic DCI alloys and the graphite nodule spacing. The J_{Ic} values were recalculated by the methods of the revised version of the ASTM Standard (ASTM E 813-87), and were found to be 5 to 8% higher than those determined by the original standard. A linear regression analysis was used to reaffirm that the fracture toughness is directly related to the graphite nodule size or spacing.

* This work performed at Sandia National Laboratories supported by the U. S. Department of Energy under contract number DE-AC04-76DP00789.

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Introduction

Previous reports (1,2) have detailed a relationship between fracture toughness and microstructure for ferritic DCI alloys. The fracture toughness was determined by using a single specimen, unloading compliance technique to measure J_{Ic} per the ASTM Standard Test Method E 813-81 (3). A new revision of this standard has been issued as E 813-87, and became available in mid-1988 (4). The methods and requirements for data acquisition have not been substantially changed in the revised standard. However, the calculation and interpretation of results has been altered significantly between the two versions of the standard. Since the data requirements were not changed, the original data could be reanalyzed using the revised standard. This recalculation of the data is important since there is the potential for the initiation fracture toughness values, J_{Ic}, to be significantly shifted.

The original calculations of J_{Ic} were used to establish a relationship between upper shelf fracture toughness and microstructure for sixteen different compositions / microstructures of ferritic DCI alloys. Since the revised standard may result in different values for J_{Ic}, it is clear that the microstructural basis for the upper shelf fracture toughness should be reexamined for the revised values. The original relationship has been used as the foundation for understanding the upper shelf fracture toughness of ferritic DCI alloys in general. A data base has been created which uses the measurements from Reference 1 as its primary source, but has been extended to include all the fracture toughness measurements available in the literature (5). It is therefore important to detail the quantitative relationship between microstructural measurements and J_{Ic}, as calculated by both versions of the standard. Further, this work has been used to support the establishment of a proposed new standard for a "premium quality" grade of DCI (6).

This new standard is being developed for high quality grades of DCI for use in such critical applications as nuclear material transportation.

Comparison of the Original and Revised Versions of ASTM E 813

ASTM E 813 Standard Test Method was developed to measure the elastic-plastic fracture toughness near the initiation of slow stable crack growth. The method involves determining the value of the J-integral which is an integral (surface or line) that encloses the crack front from one crack surface to the other. The value of J is used to characterize the local stress-strain field around the crack front. When certain conditions are met, the J-integral is path independent and can be used to specify the material's inherent resistance to extension of a preexisting flaw. The standard test method has been designed such that the conditions for path independence will be met.

A solution for the J-integral equation is presented in each version of the ASTM E 813 standard. In each version the solution to the J-integral is directly related to the specific sample geometry, and area under the load - displacement record. Thus, it is common to both versions that the load and the displacement (along the load line, also known as LLD), must be measured as a precracked specimen is loaded. Also common to both versions is the use of a compliance unloading method to monitor the crack length periodically throughout the test. A test record in which the load and load line displacement were measured, and which displays periodic unloadings (to determine the compliance) contains all the information necessary to be analyzed by either version of E 813. Thus a test record which was originally taken in order to determine the J_{Ic} per E 813-81, can be reanalyzed to evaluate J_{Ic} to the revised standard (E 813-87). A test record which is typical of the original load - LLD data (with periodic load drops) is shown in Figure 1.

The data from Figure 1 are used to generate a plot of J versus change in crack length. The area under the curve at any specific point is directly related to the value of J. The crack length can be determined at any point where there is an unloading. The inverse of the compliance is directly related to the crack length. Thus, from the load - LLD test record (e.g., see Figure 1) a plot of J versus change in crack length can be determined.

The basis of the relationship between the compliance and crack length for the standard specimens was not changed between the original and the revised versions of E 813. Thus, the calculation of the change in crack length does not vary between the two versions. In contrast, the exact equations used to calculate the value of J (at any point during the test) differ in the two versions. In the original version of E 813, an approximation was employed in which the total J was calculated directly from the full area under the load - LLD curve. In the new E 813, the elastic and plastic portions of J are separated, which in turn also requires separation of the load - LLD areas into elastic and plastic regions. Further, the exact method of handling the corrections to the J calculation due to crack growth during the test, varies between the old and the new versions. In spite of these differences, the values calculated for J (for our alloys) by the two methods differed only slightly. Figure 2 shows a typical example of the J-change in crack length calculation for the two versions of E 813. For small amounts of crack growth, the two calculations yielded essentially identical values of J. As the crack extended, the difference between the two calculation methods increased, but the difference never amounted to more than about 5%. Since there is only a slight difference between the J values calculated by either method, the details of the calculations will not be presented. The reader who is interested in the particulars of these computations can refer directly to the two versions of the standards (3,4).

A more pronounced difference between the two versions of E 813, lies in the curve fit procedure and the methods used to select a value for J_{Ic}. The original standard established a theoretical blunting line as being equal to:

$$J = 2\,\sigma_y \cdot \Delta a \qquad \text{Eqn. 1}$$

where σ_y is the effective flow strength of the alloy (= 1/2· (yield strength + ultimate strength)), and Δa is the change in crack length. Offset lines through Δa values (@J=0) of 0.15mm and 1.5mm which are parallel to the blunting line were used to establish limits on the data to be used in the curve fitting process. The J-Δa values between the two offset lines were then fit with a least squares straight line. The crack-extension resistance as a function of stable crack extension (i.e. the "R-curve") is thus assumed to be of the form:

$$J = b + m \cdot \Delta a \qquad \text{Eqn. 2.}$$

This straight line was then extrapolated back through the blunting line. The intersection of the straight line fit through the data and the blunting line became the conditional value, J_Q, for the initiation fracture toughness. The J_Q value became the valid J_{Ic} when all the requirements as listed in the test standard were met (e.g. specimen size, crack front straightness, no cleavage, etc.). Figure 3 shows an example of the J-Δa data, with the blunting line, the two offset lines, and the straight line fit through the valid data.

The curve fitting procedure employed by the new version of E 813 is quite different. The region of valid data is essentially unchanged, while a few more restrictions are imposed to make sure the J-Δa are properly distributed throughout the entire valid region. The most pronounced change is the power law fit of the data (in the valid region) in place of the linear fit. The R-curve is thus assumed to be of the form:

$$J = C_1 \cdot \Delta a^{C_2} \qquad \text{Eqn. 3.}$$

An additional offset line, through 0.2mm, is used in E 813-87. J_Q is the intersection of this offset line with the power law fit through the data. Rules similar to those in the original standard are used to qualify the conditional value as the initiation fracture toughness, J_{Ic}. Figure 4 shows the power law fit of the same data presented in Figure 3. For the example shown in Figures 3 and 4, the J_Q value met all the criteria necessary to be validated as J_{Ic}. The value for J_{Ic} for this sample increased from 53.4 kJ/m^2 to 56.0 kJ/m^2 (or about a 5% increase).

Results of J_{Ic} Calculations for the Series of DCI Alloys

All of the original data for the ferritic DCI fracture toughness tests were reanalyzed to compare the J_{Ic} values calculated from E 813-87 with those computed according to E 813-81. Table 1 provides a summary of the results. Figure 5 is a graphic summary in which the "new" J_{Ic} numbers (from E 813-87) are plotted against the "old" J_{Ic} values (from E 813-81). The data have been fit with a least squares straight line (with an r^2 = 0.991). A reference line in the figure shows where a perfect 1 to 1 match between the original and revised methods would lie (i.e., the two methods would yield exactly the same values for J_{Ic}). The magnitude of the difference between the reference line and the straight line through the data increases slightly with increasing J_{Ic}. The fractional change in J_{Ic} is largest for the smallest values of J_{Ic}, showing that the change in calculational method has the biggest percentage effect for the lowest toughness samples. The fractional change is relatively modest and is in the range of 5 to 8%. Further, the shift caused by changing computational methods seems to be well behaved and systematic.

Relationship of Fracture Toughness to Microstructure

Previously, a large number of compositional and microstructural features were measured directly on samples from each fracture toughness specimen (1). The coupons for metallography and compositional analysis were taken from a region as close as possible to the fracture surface of the previously tested toughness specimens. The complete set of measurements is reproduced in Table 2. As described in Reference 1, a general linear relationship was assumed to exist between the measured J_{Ic} and all the compositional / microstructural features listed in Table 2. A multiple regression analysis was used to test this hypothesis. It was determined that the changes in composition (listed in Table 2) do not significantly affect the upper shelf fracture toughness. Similarly, the ferrite grain size and the volume fraction of graphite do not have a statistically important role in determining the J_{Ic}. Once the statistically insignificant relationships were removed, the final model could be represented as:

$$J_{Ic} = a + f \cdot L \qquad \text{Eqn. 4}$$

where, a and f are constants, and L stands for a dimension which is representative of the nodule distribution. This nodule distribution dimension can be expressed in terms of D_V, D_A, λ_V, or Δ_A. D_V and D_A are measurements of the "3-D" and "2-D" average nodule diameter, and λ_V and Δ_A are average spacings between the nodules in terms of "3-D" and "2-D" measurements. The fracture toughness can be predicted equally well by any of the these inter-related parameters. Δ_A is a straightforward and reproducible measurement:

$$\Delta_A = 0.5 / (N_A{}^{1/2}) \qquad \text{Eqn. 5}$$

where N_A is the number of nodules per unit area (i.e., #/mm^2) on a random plane. N_A is a number which is commonly used to comparatively describe graphite nodule distributions from sample to sample of DCI. Since Δ_A is simply related to N_A, and also is an accurate measure of nodule spacing, it is recommended as a suitable gauge for characterizing the nodule distribution.

The fracture toughness / microstructural relationships are presented in terms of Δ_A for values of J_{Ic} determined by both versions of E 813. A plot of J_{Ic} values determined by E 813-81 versus Δ_A, is shown in Figure 6. The linear equation relating J_{Ic} and Δ_A is presented in the figure, along with parameters which show the statistical significance of the fit. Figure 7 shows the same information for revised values of J_{Ic} determined by E 813-87, as it relates to Δ_A. The "quality of fit", which is shown by the standard deviation (r^2), the F-test, and the standard error from the regression, is essentially the same for both types of J_{Ic} calculations. The results from the fits of J_{Ic} from the two versions of E 813 as a function of Δ_A, are shown together in Figure 8.

The equations relating J_{Ic} (from both versions of E 813) with all the measures of nodule size and spacing are listed in Table 3. Also listed are the statistical parameters which provide a measure of the quality of fit, and the level of confidence in the calculated relationship.

Discussion

The ASTM Standard Test Method governing the determination of J_{IC} has undergone a significant revision from the original (E 813-81) to the current version (E 813-87). Changes have been made in the analysis of load-LLD data, and the calculation of J versus crack extension. Although the method of calculating J was changed, the effect of the changes was extremely small for all of the samples investigated in this study. The differences in calculated J values were insignificant (less than 0.5%) for all crack extensions less than 0.5mm. The difference increased somewhat with crack length, but never exceeded more than about 5% in the valid data range of crack growth (i.e., up to about 1.7 mm of measured crack extension). The two methods for calculating J did not have a measurable effect on the determination of the initiation value, J_{IC}.

The original and revised versions of E 813 differ substantially in the manner in which the J-Δa curve is fit, and in the method used to define crack initiation. The original used a straight line fit, which was extrapolated back to the blunting line to define the initiation value for J_{IC}. The new version employs a power law fit of the data, and uses the intersection of the power law fit with an offset line showing 0.2 mm of crack growth. These different methods did indeed have a measurable effect on the determination of J_{IC} for the series of DCI alloys. The J_{IC}s calculated by the new version (E 813-87) show an increase of 5 to 8% over those determined by the old (E 813-81) method.

The relationship between fracture toughness and the composition / microstructure is similar for the J_{IC} values calculated by either method. The only statistically significant linear relationships which could be determined show that the fracture toughness is directly dependent on the graphite nodule distribution. Nodule size and spacing are not independent (for a given volume fraction of graphite), and thus either can be used to represent the nodule distribution. Further, for the spherical particles involved in DCIs, 2-dimensional and 3-dimensional averaging type measurements seem to provide essentially the same information (for additional discussion of this refer to Reference 1), and thus can be used with equal success in the correlation to fracture toughness.

Conclusions

1. The J-Δa behavior is essentially unaffected by using either version of E 813.
2. The major difference between the original and revised versions of E 813 is in the type of equation used to fit the (valid) data, and in the definition of J_{Ic}.
3. For the set of DCI alloys examined, using the new version (E813-87) causes the J_{Ic} values to increase by 5 to 8% over the values determined by the original method (E813-81).
4. The microstructural basis for fracture toughness has been reaffirmed. J_{Ic} values (from both E 813-81 and E 813-87) were shown to be linearly related to the graphite nodule distribution. The nodule distribution can be represented by two- and three-dimensional measurements of the average size and spacing.

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3. "ASTM E 813-81: Standard Test Method for J_{Ic}, A Measure of Fracture Toughness," 1986 Annual Book of ASTM Standards, Section 3, Metals Test Methods and Analytical Procedures, 3.01, American Society for Testing and Materials, Philadelphia, 1986, pp. 768-786.

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5. P. McConnell and P. Lombrozo, "Ductile Iron Data Base - Correlations Between Microstructure and Fracture Toughness," Sandia Report SAND86-7163, Sandia National Laboratories, Albuquerque, NM, February 1987.

6. "ASTM A 874 Draft Specification: Specification for Ferritic Ductile Cast Iron Castings Suitable for Low Temperature Service"

Table 1.

J_{Ic} fracture toughness data as calculated from the two versions of E 813, for a group of ferritic DCI alloys.

Sample	J_{Ic}{E 813-81}* (kJ/m^2)	J_{Ic}{E 813-87} (kJ/m^2)
1U	72.1	73.2
2U	61.6	67.2
3U	55.3	59.2
4U	79.9	85.6
5U	74.8	79.0
6U	68.1	71.6
7U	77.4	82.1
8U	70.4	74.6
1L	53.4	56.0
2L	58.7	64.3
3L	29.6	31.0
4L	49.6	51.7
5L	45.4	50.6
6L	44.5	45.2
7L	24.0	28.4
8L	31.9	34.1

* Values listed here differ from those presented in Reference 1 because of a correction in the value for net sample thickness.

Table 2a.

Microstructural features measured on the DCI alloys used in this study.

Sample	$V_v^{graphite}$ (%)	$d^{ferrite}$ (mm)	$\bar{D}_v$ (mm)	$\bar{\lambda}_v$ (mm)	N_A (number mm^{-2})	$\bar{D}_A$ (mm)	$\bar{\Delta}_A$ (mm)	$V_v^{pearlite}$ (%)	Nodule type
1U	11.4	0.071	0.167	0.755	19.9	0.085	0.118	< 5	100%-type II
2U	13.9	0.076	0.123	0.513	23.2	0.087	0.104	< 5	100%-type II
3U	13.8	0.057	0.134	0.299	71.3	0.050	0.059	0	60%-type II 40%-type III
4U	13.8	0.050	0.167	0.821	13.2	0.115	0.138	< 10	100%-type II
5U	10.2	0.057	0.136	0.808	13.0	0.100	0.139	< 10	100%-type II
6U	10.7	0.047	0.144	0.547	26.5	0.072	0.097	< 5	70%-type II 30%-type III
7U	13.0	0.050	n.a.	n.a.	17.7	0.097	0.119	0	100%-type II
8U	11.6	0.041	n.a.	n.a.	22.1	0.082	0.106	0	100%-type II
1L	12.7	0.029	0.078	0.287	75.1	0.046	0.058	0	90%-type I 10%-type II
2L	10.2	0.031	0.093	0.448	39.2	0.057	0.080	< 5	90%-type I 10%-type II
3L	14.7	0.032	0.052	0.148	176.2	0.033	0.038	0	90%-type I 10%-type II
4L	14.5	0.032	0.088	0.263	67.3	0.052	0.061	< 5	90%-type I 10%-type II
5L	13.0	0.029	0.075	0.246	99.3	0.041	0.050	0	90%-type I 10%-type II
6L	9.9	0.028	0.052	0.198	209.7	0.025	0.035	0	50%-type I 50%-type II
7L	8.9	0.026	0.031	0.159	353.2	0.018	0.027	0	90%-type I 10%-type II
8L	13.2	0.030	0.051	0.157	169.1	0.032	0.038	0	90%-type I 10%-type II

Table 2b.

Composition of the DCI alloys used in this study.

Sample	Composition						
	C (wt %)	Si (wt %)	Ni (wt %)	S (wt %)	Cu (wt %)	Cr (wt %)	Mn (wt %)
1U	2.53	1.71	0.54	0.027	0.092	0.07	0.23
2U	2.82	1.64	0.66	0.018	0.085	0.08	0.25
3U	2.54	3.49	0.58	0.016	0.086	0.08	0.24
4U	2.96	1.75	0.97	0.027	0.088	0.08	0.24
5U	2.97	1.70	0.76	0.024	0.083	0.08	0.24
6U	2.56	3.20	0.95	0.013	0.091	0.08	0.24
7U	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
8U	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1L	2.88	1.11	0.96	0.022	0.21	0.14	0.26
2L	2.83	1.07	1.08	0.024	0.20	0.13	0.25
3L	2.71	2.03	0.97	0.015	0.22	0.14	0.26
4L	3.06	1.16	1.42	0.022	0.21	0.14	0.23
5L	3.09	1.11	1.11	0.024	0.20	0.14	0.24
6L	2.69	1.96	1.32	0.013	0.20	0.14	0.25
7L	2.93	2.10	0.79	0.010	0.20	0.14	0.26
8L	2.91	2.07	0.94	0.007	0.21	0.14	0.25

Table 3.

Linear regression fit of J_{Ic} fracture toughness (as calculated from the two versions of E 813) by measured values representing the graphite nodule distribution. The linear equation is of the form: $J_{Ic} = a + f \cdot L$, where $L = D_V$, D_A, λ_V, or Δ_A.

J_{Ic} Standard Used	Measured Feature (mm)	Constant a (kJm^{-2})	Coefficient f ($kJm^{-2}mm^{-1}$)	r^2	Standard Error of Regression (kJm^{-2})	F-test
E 813-87	Δ_A	24.1	443	0.897	6.07	$F_{1,14}=122$
E 813-87	D_A	23.6	581	0.887	6.36	$F_{1,14}=110$
E 813-87	λ_V	29.8	67.4	0.863	6.89	$F_{1,12}=75.7$
E 813-87	D_V	20.6	365	0.863	6.89	$F_{1,12}=75.8$
E 813-81	Δ_A	22.0	425	0.891	5.99	$F_{1,14}=115$
E 813-81	D_A	21.6	555	0.875	6.44	$F_{1,14}=97.6$
E 813-81	λ_V	27.3	65.0	0.864	6.63	$F_{1,12}=76.1$
E 813-81	D_V	18.3	355	0.875	6.36	$F_{1,12}=83.7$

For a 99% confidence level, $F_{1,14} > 8.86$ and $F_{1,12} > 9.33$.

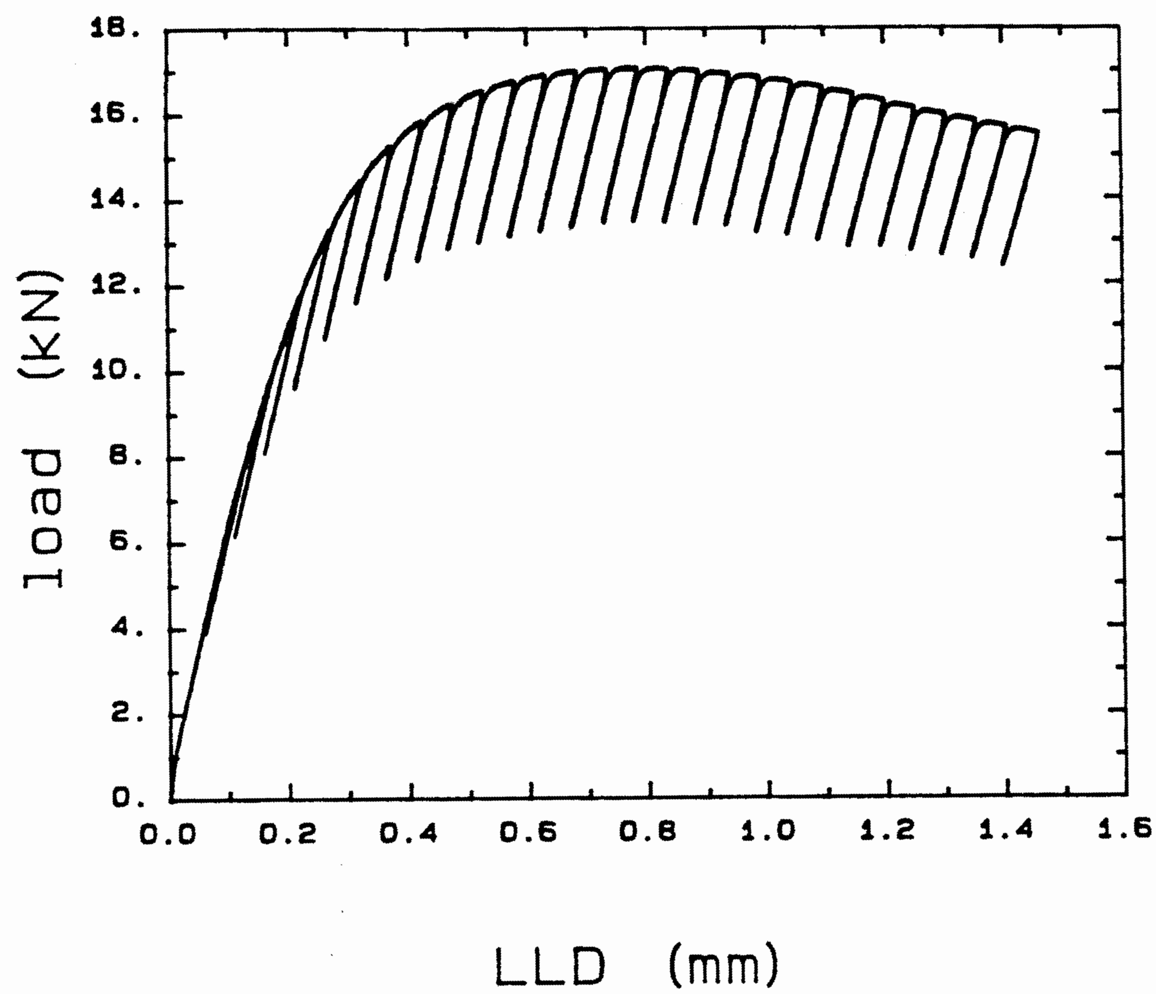

Figure 1. A typical load - LLD (load line displacement) record for a single specimen unloading compliance J-integral test (to either E 813-81 or E 813-87). [Sample 1U, B_{net} = 20.6 mm, W = 50 mm, temp. = 25°C]

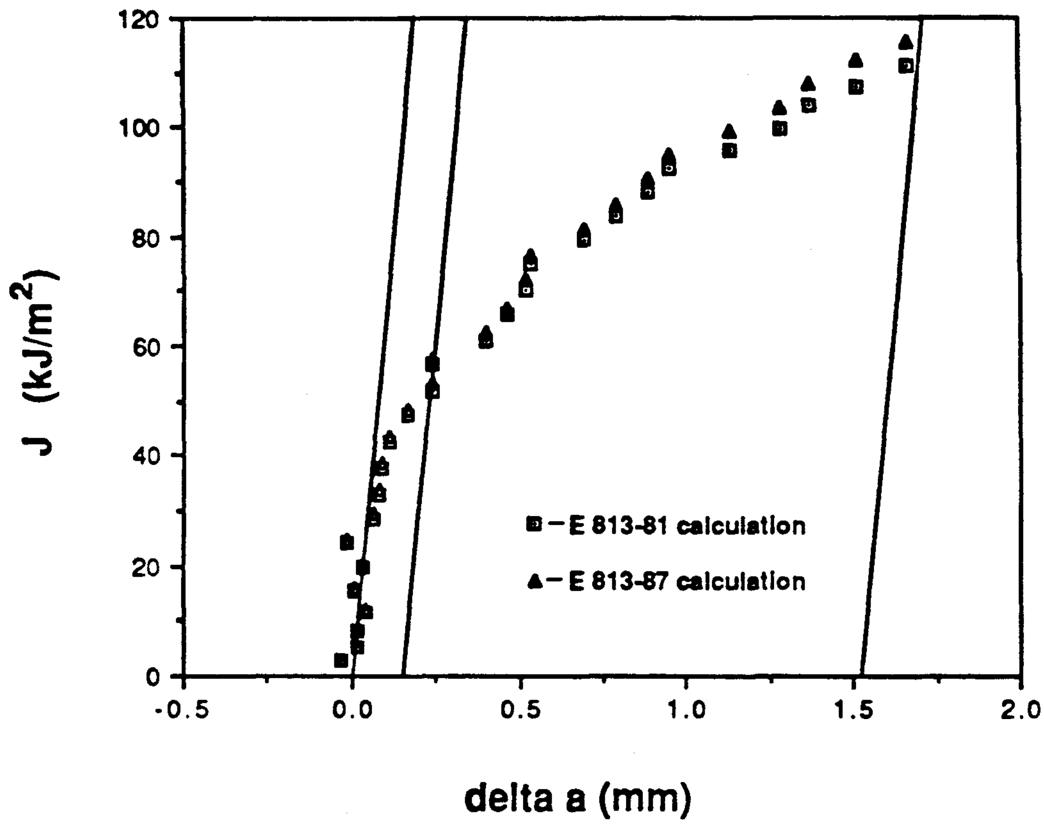

Figure 2. J versus crack growth behavior for a typical sample as calculated by the two versions of ASTM E 813. [Sample 1U, B_{net} = 20.6 mm, W = 50 mm, temp. = 25°C)]

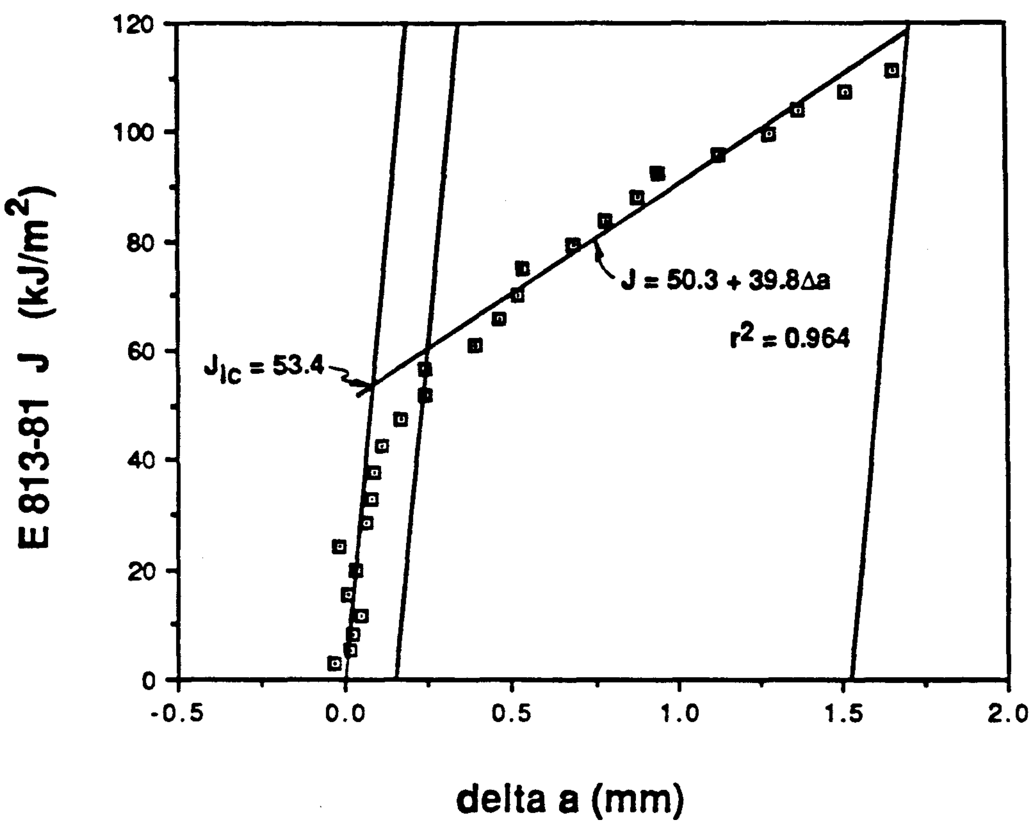

Figure 3. Straight line fit of valid portion of the J-Δa data, and determination of J_{Ic}, according to ASTM E 813-81. [Sample 1U, B_{net} = 20.6 mm, W = 50 mm, temp. = 25°C]

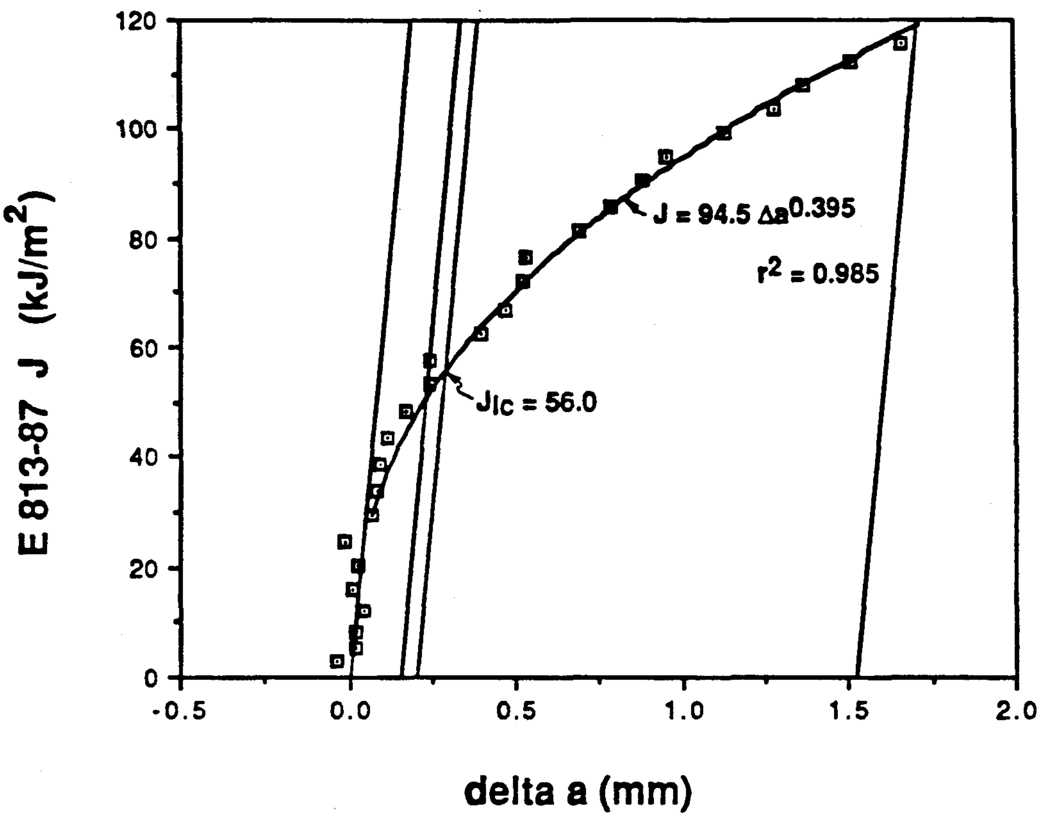

Figure 4. Power law fit of the valid J-Δa data, and determination of J_{Ic}, according to ASTM E 813-87. [Sample 1U, B_{net} = 20.6 mm, W = 50 mm, temp. = 25°C]

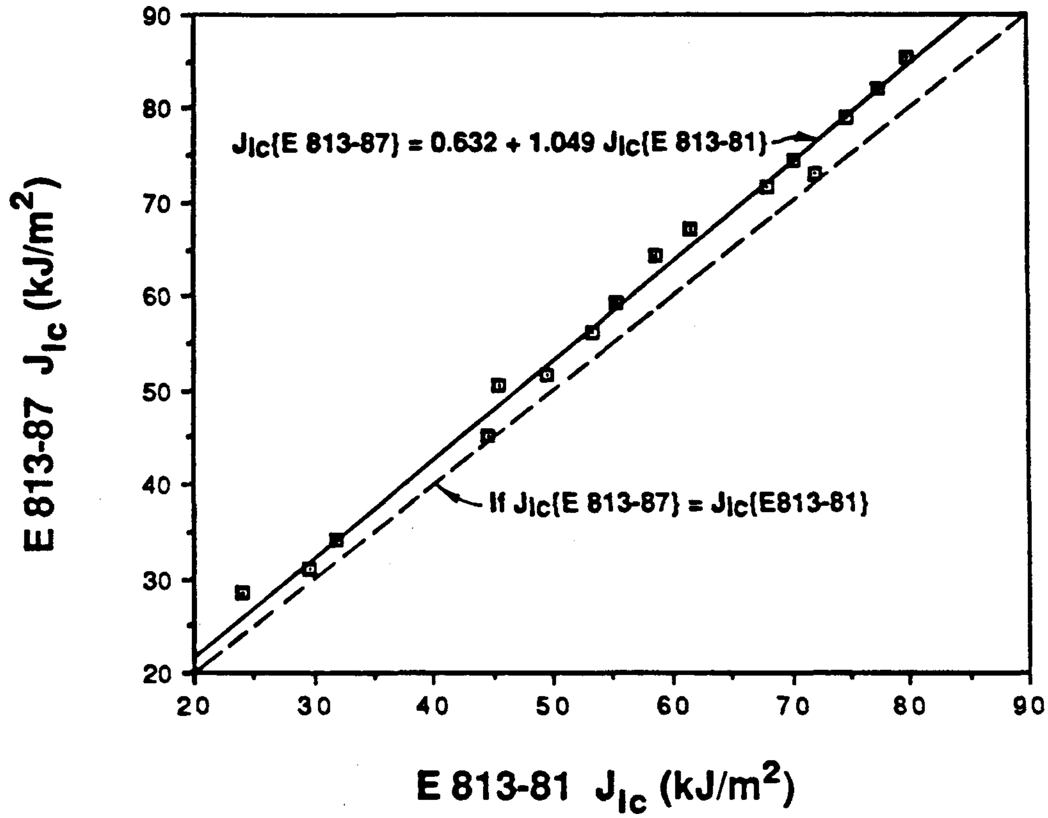

Figure 5. J_{Ic} determined by the new version (E 813-87), plotted against J_{Ic} as calculated by the original version (E 813-81) for the set of ferritic DCI alloys.

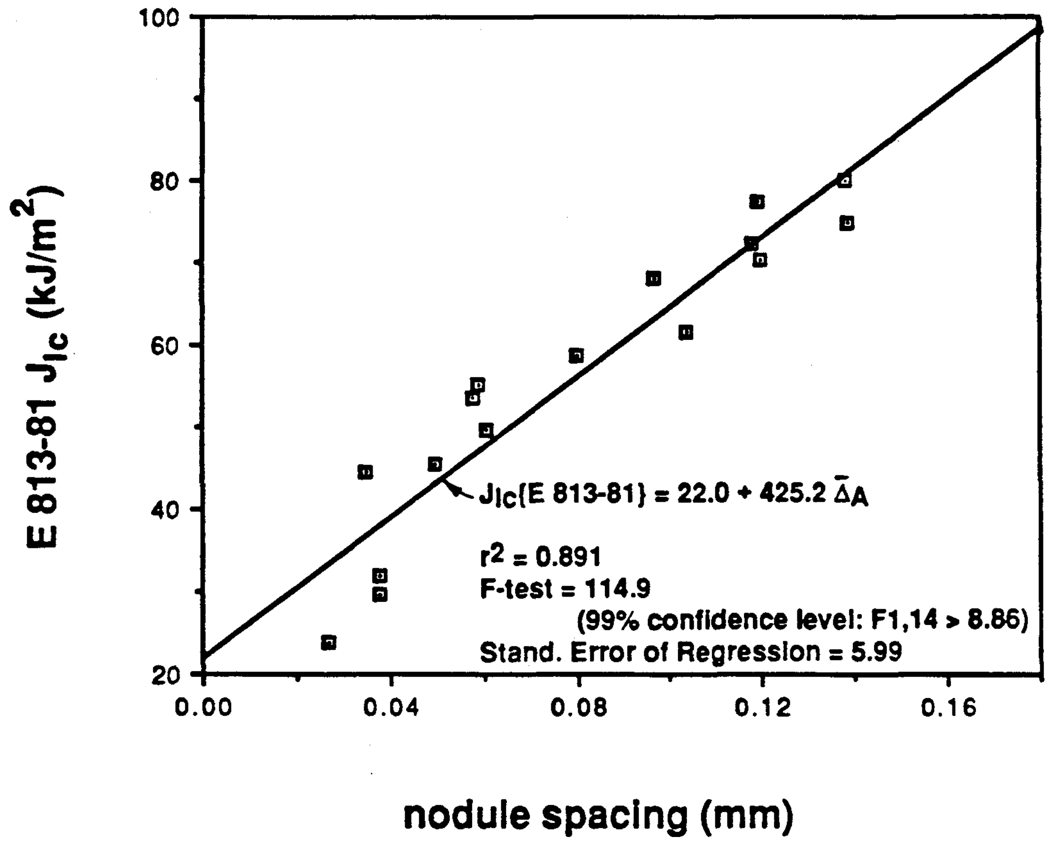

Figure 6. Results of the linear regression fit of the J_{Ic} data (calculated to the original version: E 813-81) for the set of DCI alloys, showing the fracture toughness related to average graphite nodule spacing (determined by a two-dimensional measurement).

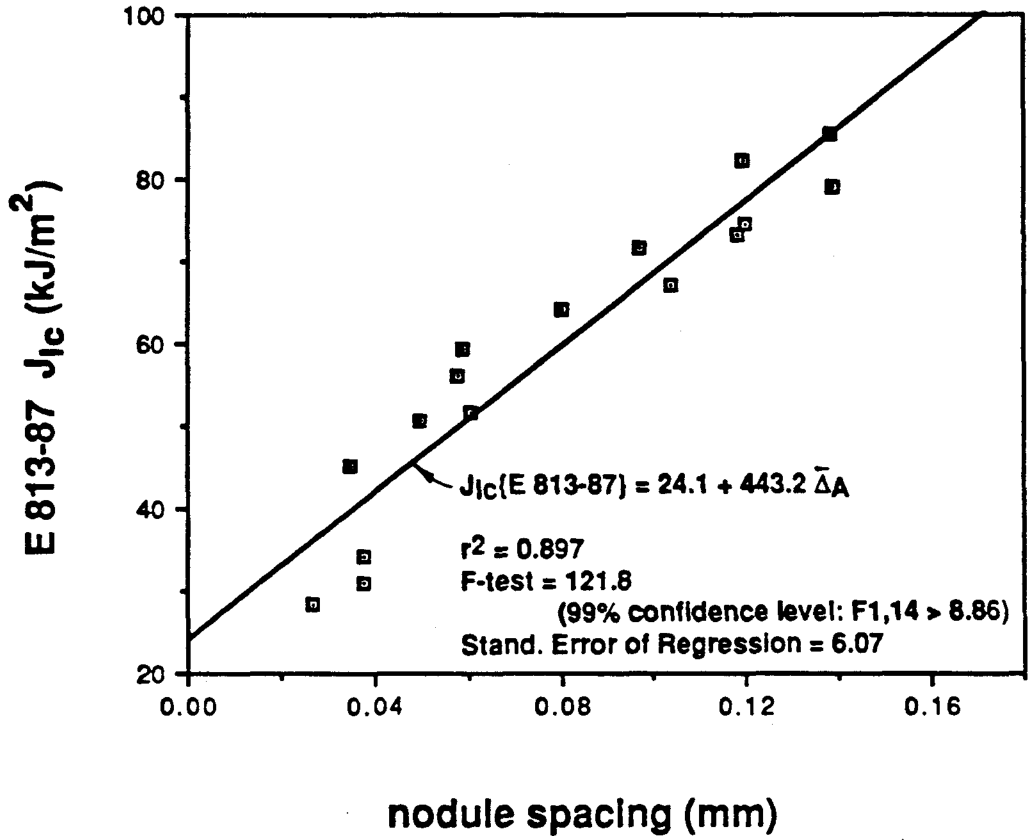

Figure 7. Results of the linear regression fit of the J_{Ic} data (calculated to the revised version: E 813-87) for the set of DCI alloys, showing the fracture toughness related to average graphite nodule spacing (determined by a two-dimensional measurement).

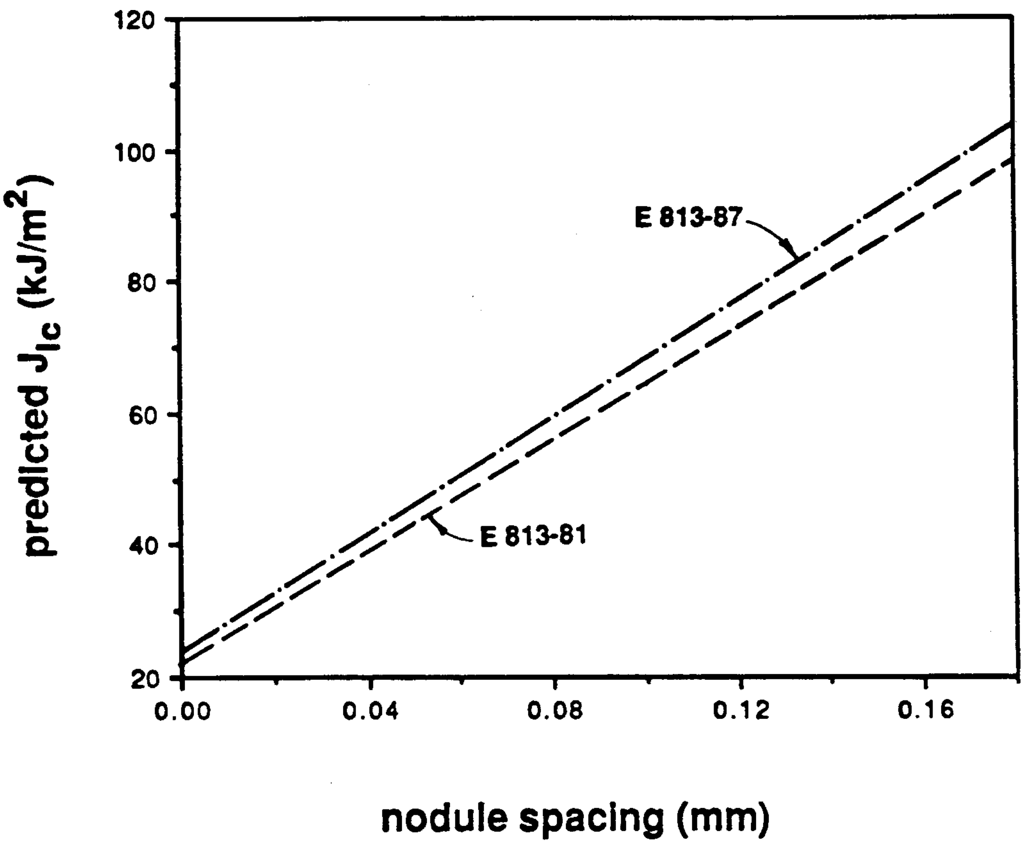

Figure 8. Comparison of the linear regression fit of the fracture toughness for the set of DCI alloys in which the J_{Ic} values were determined by the two versions of the ASTM E 813.