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Fracture toughness (K_{Ic}) values of some cast irons

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FRACTURE TOUGHNESS K_{Ic} VALUES OF SOME CAST IRONS

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FRACTURE TOUGHNESS (K_{Ic}) VALUES OF SOME CAST IRONS

1. NOTATION

Both SI and British units are quoted.

Unless otherwise stated, and where relevant, the notation relates to static as opposed to dynamic properties.

Additional notation used in the appendices is defined in the appropriate appendix.

A	area of appropriate/typical cross-section of graphite nodule	m^2	in^2
B	test piece thickness (see Equation (2.1))	m	in
cv	coefficient of variation, defined as standard deviation divided by mean (see tables in Section 5.3 and Appendices E and F)		
E	modulus of elasticity	N/m^2	lbf/in^2
G_{Ic}	plane strain Mode I toughness	N/m	lbf/in
HB	Brinell Hardness		
HB_{30}	Brinell Hardness (30 kgf)		
HV	Vickers Hardness		
HV_{50}	Vickers Hardness (50 kgf)	N/m	$lbf/in^{3/2}$
J_d	dynamic value of J -integral	N/m	$lbf/in^{3/2}$
J_{Ic}	critical Mode I value of J -integral in plane strain	N/m	lbf/in
K	crack-tip stress-field-intensity factor	$N/m^{3/2}$	$lbf/in^{3/2}$
$\dot{K}$	rate of increase of stress intensity factor	$N/(m^{3/2}s)$	$lbf/(in^{3/2}s)$
K_c	plane-stress fracture toughness (critical value of stress intensity in plane stress)	$N/m^{3/2}$	$lbf/in^{3/2}$
K_d	dynamic plane-stress fracture toughness (critical value of dynamic stress intensity in plane stress)	$N/m^{3/2}$	$lbf/in^{3/2}$
K_I	stress intensity factor	$N/m^{3/2}$	$lbf/in^{3/2}$
K_{Ic}	plane-strain fracture toughness in Mode I (critical value of stress intensity in plane strain)	$N/m^{3/2}$	$lbf/in^{3/2}$
$K_{Ic l}$	lower-shelf K_{Ic}	$N/m^{3/2}$	$lbf/in^{3/2}$
$K_{Ic Tr}$	transition region K_{Ic}	$N/m^{3/2}$	$lbf/in^{3/2}$
$K_{Ic u}$	upper-shelf K_{Ic}	$N/m^{3/2}$	$lbf/in^{3/2}$
K_{Id}	dynamic plane-strain fracture toughness in Mode I (critical value of stress intensity in plane strain)	$N/m^{3/2}$	$lbf/in^{3/2}$

K_{Jc}	fracture toughness calculated from J -integral	N/m ^{3/2}	lbf/in ^{3/2}
K_{Jd}	dynamic fracture toughness calculated from dynamic value of J -integral, J_d	N/m ^{3/2}	lbf/in ^{3/2}
K_{J1c}	plane-strain fracture toughness in Mode I calculated from J_{1c}	N/m ^{3/2}	lbf/in ^{3/2}
K_{JQ}	plane-strain fracture toughness in Mode I calculated from J -integral value obtained from test where no stable crack growth was observed	N/m ^{3/2}	lbf/in ^{3/2}
K_{max}	fracture toughness based on maximum tensile load in test, see Appendix A	N/m ^{3/2}	lbf/in ^{3/2}
K_Q	conditional plane-strain fracture toughness, see Appendix A	N/m ^{3/2}	lbf/in ^{3/2}
k_1	statistical factor incorporating coefficients of variation of samples		
n	number of values in sample		
P	percentage pearlite content		
s	standard deviation	N/m ^{3/2}	lbf/in ^{3/2}
Sh	nodule shape (defined in Equation (3.1))		
$t_{\alpha, \nu}$	Student's t -distribution value for a confidence level α and ν degrees of freedom (see Table 1.8 and Equation (A2.1) of ESDU 91041 [†])		
T	temperature	°C	°F
T_1	temperature at onset of brittle-to-ductile transition region (see Section 5.2.2 and Appendix E, Section E3)	°C	°F
T_2	temperature at conclusion of brittle-to-ductile transition region (see Section 5.2.2 and Appendix E, Section E3)	°C	°F
U	circumference of appropriate/typical cross-section of graphite nodule	m	in
Δ	difference between mean and lower confidence limit (see Section 5.3.2)	N/m ^{3/2}	lbf/in ^{3/2}
Δ_1	difference between mean and lower confidence limit for sub-group (see Section 5.3.2)	N/m ^{3/2}	lbf/in ^{3/2}
Δ_2	difference between mean and lower confidence limit for parent group (see Section 5.3.2)	N/m ^{3/2}	lbf/in ^{3/2}
ΔT	temperature translation factor (see Section 5.2.2.1 and Appendix E, Section E3.3)	°C	°F
ν	Poisson's ratio		
σ_p	0.2 per cent proof stress	N/m ²	lbf/in ²
σ_{pd}	0.2 per cent dynamic proof stress	N/m ²	lbf/in ²

σ_{uts}	tensile strength	N/m ²	lbf/in ²
σ_y	yield strength	N/m ²	lbf/in ²
σ_{yd}	dynamic yield strength	N/m ²	lbf/in ²
ν	degrees of freedom		

[†] See ESDU 91041, "The statistical analysis of data form Normal distribution, with particular reference to small samples".

Suffixes

mean the suffix *mean*, applied to K_{Ic} and K_{Id} , refers to the mean fracture toughness values in the tables of Sections 8 and 9.

1.1 K_{Ic} and K Conversion Factors

For static and dynamic fracture toughness values,

$$1 \text{ MN/m}^{3/2} = 0.910\,047 \text{ ksi} \sqrt{\text{in}} = 0.910\,047 \times 10^3 \text{ lbf/in}^{3/2}.$$

Note also that,

$$1 \text{ MN/m}^{3/2} = 31.6228 \text{ N/mm}^{3/2} = 1 \text{ MPa} \sqrt{\text{m}}.$$

For rate of change of stress intensity values,

$$1 \text{ MN}/(\text{m}^{3/2}\text{s}) = 0.910\,047 \text{ ksi} \sqrt{\text{in}}/\text{s} = 0.910\,047 \times 10^3 \text{ lbf}/(\text{in}^{3/2}\text{s})$$

and

$$1 \text{ MN}/(\text{m}^{3/2}\text{s}) = 31.6228 \text{ N}/(\text{mm}^{3/2}\text{s}) = 1 \text{ MPa} \sqrt{\text{m}}/\text{s}.$$

2. NOTES

2.1 Synopsis

This Item presents static and dynamic plane-strain fracture toughness (K_{Ic} and K_{Id}) values for a variety of cast irons along with notes on fracture toughness and other related topics in linear elastic fracture mechanics (LEFM). Further topics relating to fracture mechanics are discussed in ESDU 80036*.

Within this Item a cast iron is defined as an iron-carbon alloy with a carbon content in excess of 2 per cent by weight. The main forms of cast iron produced commercially are white, grey, malleable, ductile and compacted graphite cast iron. All the cast irons described, other than white, have a microstructure that includes a graphite phase. Cast irons may also include alloying elements other than carbon.

Sections 2.2 to 2.4 give general information relating to fracture toughness testing, and provide details regarding the presentation of data in the Item.

An account of the various forms of cast iron and their fracture characteristics is given in Section 3, whilst Section 4 covers the various factors that are likely to influence the measured value of fracture toughness of a component.

The results of statistical analyses of the fracture toughness data are presented in Section 5. Two distinct types of study were conducted: the first involved developing relationships between the fracture toughness of a given material and other parameters (the Regression Analysis Method), whilst the second involved grouping given K_{Ic} values according to various criteria and finding corresponding mean K_{Ic} values for each group (the Group Analysis Method). The objective of the analyses was to obtain a *Design Allowable* K_{Ic} for a given material, assuming a 99 per cent probability of survival based on a 95 per cent level of confidence about the mean.

Section 6 lists the sources of the data on which the Item was based and some useful references.

Section 7 comprises a worked example which demonstrates how the data in the Item may be applied to a practical situation.

Static and dynamic fracture toughness data (K_{Ic} and K_{Id}) are presented in Sections 8 and 9. Also included are the test temperatures and material properties such as yield strength, tensile strength and hardness.

Appendix A provides a description of how various fracture toughness values are measured, whilst Appendix B compares K_{Ic} values measured using two variants of the *J*-integral test.

The application of the Barsom Temperature Shift technique to GGG-35.3 and GGG-40 ferritic ductile iron is demonstrated in Appendix C.

Specifications for various cast irons are given in Appendix D.

Appendix E provides details of the regression analyses performed in Section 5.2, and an outline of the Group Analysis Method (Section 5.3) is given in Appendix F.

Appendix G comprises statistical data utilised in Appendices E and F.

* ESDU 80036, "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

2.2 General Notes

Fracture toughness values are used within LEFM to determine the static strength of components containing fatigue cracks or defects. Such flawed components will fail under a slowly increasing applied load when the stress intensity factor, K , reaches a critical value. In relatively thick sections, the crack may propagate rapidly and unstably through the component, causing sudden, complete failure. The critical value in this case is called the “plane-strain fracture toughness”, designated K_{Ic} , which is a constant material property with respect to the specified test environment. It represents static loading conditions. The dynamic plane-strain fracture toughness is denoted as K_{Id} (see Section 4.7 for accepted definitions of static and dynamic loading rates).

In thin sections or the more ductile materials, the point of instability is less well-defined and depends on crack tip plasticity, and component thickness and other geometrical aspects (see also Section 5.1 of ESDU 80036). The results of tests on thinner sections are described simply as “fracture toughness” values (without the qualification “plane-strain”) and are designated K_c (K_d for dynamic loading conditions). The plane-strain K_{Ic} value for a given material is always less than the corresponding K_c value and therefore represents a conservative choice for the designer.

2.3 Test Conditions

Fracture toughness testing of cast irons has posed numerous difficulties for researchers, some of which are discussed in Section 3.

The data in this Item, unless otherwise indicated, have been taken from tests performed in non-corrosive environments at temperatures between -150 and 24°C (-238 and 75°F) for static testing, and varying from -100 to 66°C (-148 to 151°F) for dynamic testing, on specimens cut from various forms of castings. Some of the test pieces were taken from in-service components. The tests have been carried out in accordance with standards issued by the American Society for Testing and Materials or the British Standards Institution (see References 37 and 39). Briefly, these tests involve applying a steadily increasing load to fracture a specimen containing a machined notch that has been lengthened and sharpened by fatigue cracking. Further information on testing is given in ESDU 80036. The standards place tight controls over various aspects of toughness testing, one of which is a minimum specimen thickness requirement to ensure plane-strain conditions. The minimum value is given by the equation:

$$B \geq 2.5 \left(\frac{K_{Ic}}{\sigma_y} \right)^2, \quad (2.1)$$

where B is the specimen thickness, and σ_y is the material yield strength.

Meeting this requirement may involve using very thick specimens. For some tests, this stipulation is not met and the results are invalid according to the standards.

This Data Item includes plane-strain K_{Ic} values that have been calculated by the relevant researchers from J_{Ic} values. The path independent J -contour integral, or line integral, is applied to both elastic and plastic behaviour and its value depends upon the near-crack-tip stress-strain field. A K_{Ic} value determined from a measured J_{Ic} value is designated K_{JIc} .

The relationship between J_{Ic} and K_{JIc} is given by Equation (2.2) which is valid under linear-elastic plane-strain conditions.

$$J_{Ic} = G_{Ic} = \frac{(1 - \nu^2)}{E} K_{JIc}^2. \quad (2.2)$$

Equations (2.1) and (2.2) are also applicable to dynamic toughness. In such instances the static parameter is replaced with its dynamic equivalent.

Owing to the generally non-linear behaviour of cast iron under a tensile load, measurement of the modulus of elasticity poses practical difficulties. Fracture toughness values derived from the *J*-integral in this Data Item, unless noted otherwise, are either quoted directly from the relevant publication, or were calculated using the modulus of elasticity provided by the authors. The assumption was made that an accurate modulus of elasticity value was measured in each instance by the appropriate researcher.

A further point to note is that tensile test standards specify that an adjoining tensile test piece be cast in conjunction with the appropriate component. The tensile properties measured from such specimens, which are generally relatively small in size, can be considerably higher than the actual properties in some regions of the component. Such variation is particularly significant in large or thick components, and should be taken into consideration.

2.4 Presentation of Data

The results of the fracture toughness tests evaluated are tabulated in Sections 8 and 9. Details quoted, where available, include chemical composition, test temperature, heat treatment, proof stress, tensile strength and hardness. Where two values of thickness appear in the column headed “F&T” (Form and Thickness), the first value refers to the thickness of the test specimen while the second value refers to the thickness of the casting from which the test specimen was taken. Where only a single thickness value appears in the column, it refers to the thickness of the test specimen.

As mentioned in Section 2.3, some of the K_{Ic} values in this Item have been derived from J_{Ic} values. Such values are presented in italics in the tables.

Where the ambient temperature at which testing was conducted is not indicated in the derivation, a value of 21°C (70°F) has been assumed.

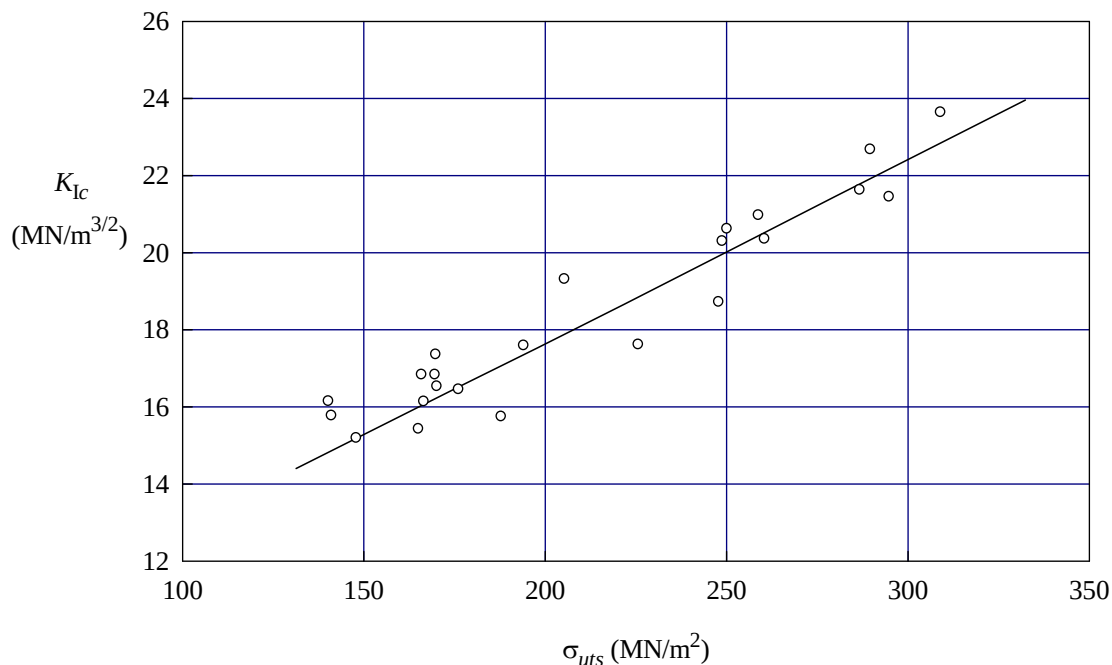
The static data in this Item relate to cases where the rate of increase of stress intensity factor corresponds to that specified in the standard test procedure (Reference 37), that is 0.55 to 2.75 MN/(m^{3/2}s) (500 to 2500 lbf/(in^{3/2}s)).

The dynamic data, unless noted otherwise, conform to the requirements of the rapid load plane-strain fracture toughness provision in Reference 37. This procedure relates to testing at a rate of increase in stress intensity factor greater than 2.75 MN/(m^{3/2}s) (2500 lbf/(in^{3/2}s)).

3. TYPES OF CAST IRON AND THEIR FRACTURE TOUGHNESS CHARACTERISTICS

3.1 Grey Cast Iron

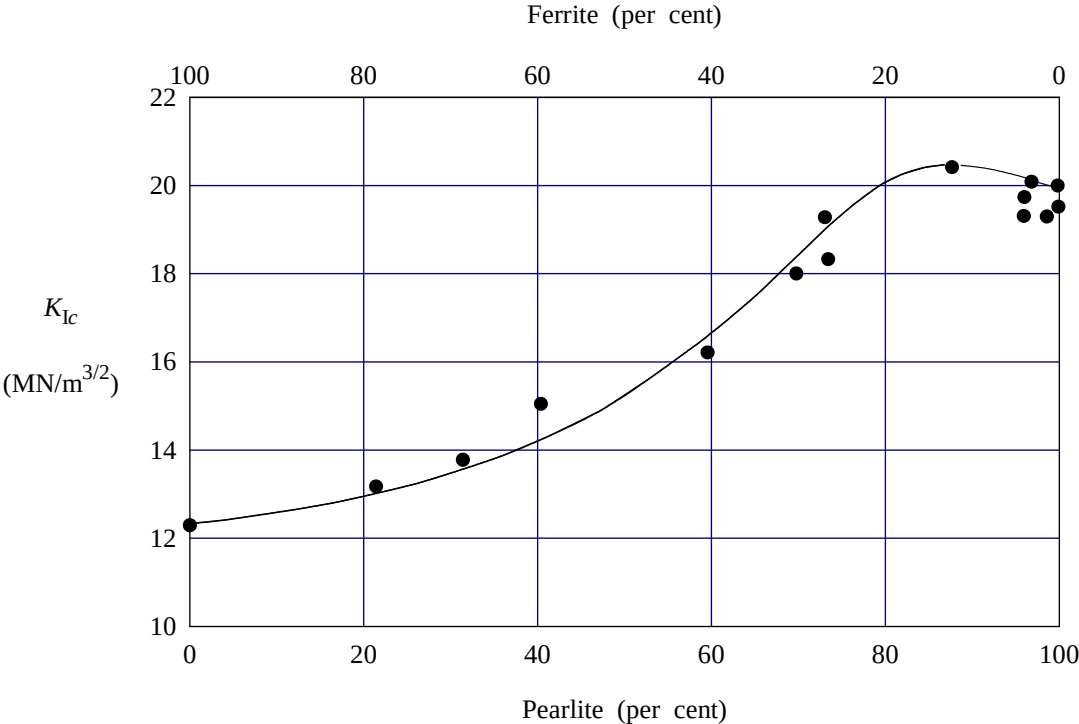
Grey cast iron is the cheapest and most widely used form of cast iron. The silicon content in such irons promotes the formation of graphite flakes which act as stress raisers, leading to relatively low fracture toughness. Tensile failure in grey cast irons results from the fracture of the graphite flakes, with minimal plastic deformation. The ultimate strength of grey cast iron is generally very close to the yield strength, and its value is often quoted as the yield strength by researchers when measuring fracture toughness. Research indicates that an increase in tensile strength of grey cast iron generally correlates with an increase in fracture toughness, see Sketch 3.1, a trend that is opposite to the general observation for engineering materials. An increase in pearlite content has also been shown to have beneficial effects on the toughness of grey cast irons, see Sketch 3.2.



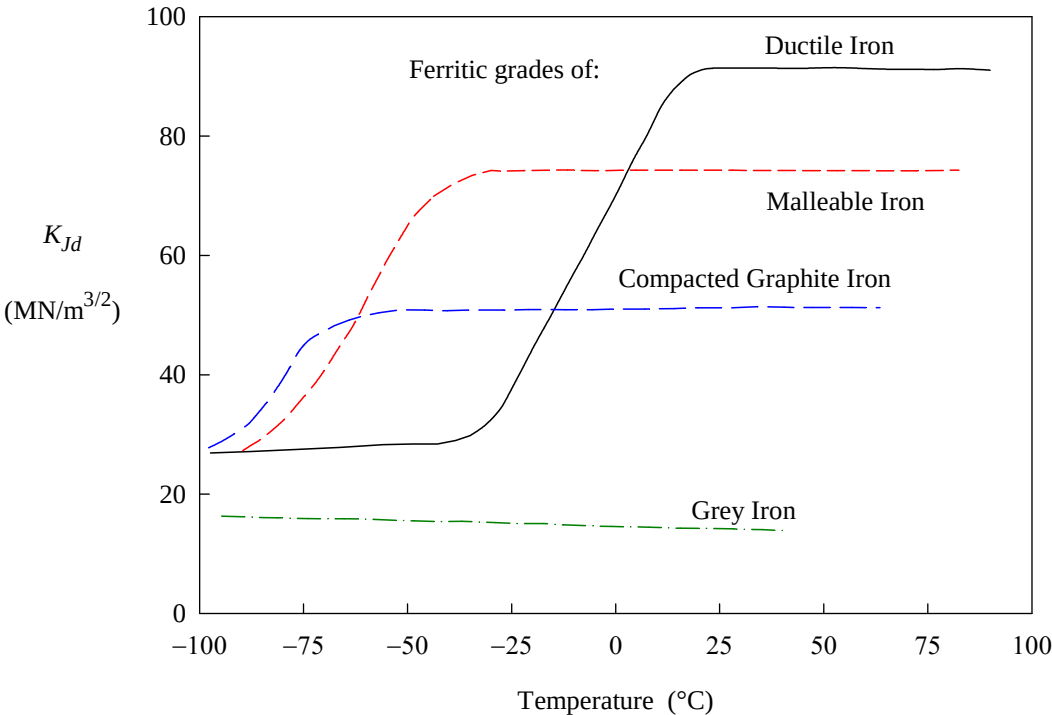
Sketch 3.1 Variation of fracture toughness with tensile strength for grey cast iron at room temperature (Reference 34)

It is difficult to determine accurately the point of crack extension in grey cast iron as a significant amount of stable crack growth precedes fracture. For this reason, fracture toughness of grey cast iron is generally described in terms of either K_Q or K_{max} . The former is considered to be a more conservative and reasonable estimate of K_{Ic} (Derivation 19), and is used in this Data Item where noted.

No brittle-to-ductile toughness energy transition is apparent for grey cast iron as the fracture process dissipates minimal energy via matrix deformation, even at temperatures where the matrix is ductile. This is because the graphite flakes always fail in a brittle manner. A gradual decrease in fracture toughness with increasing temperature, as the strength decreases, is noted for grey irons with both ferritic and pearlitic microstructures (see Sketches 3.3 and 3.4).

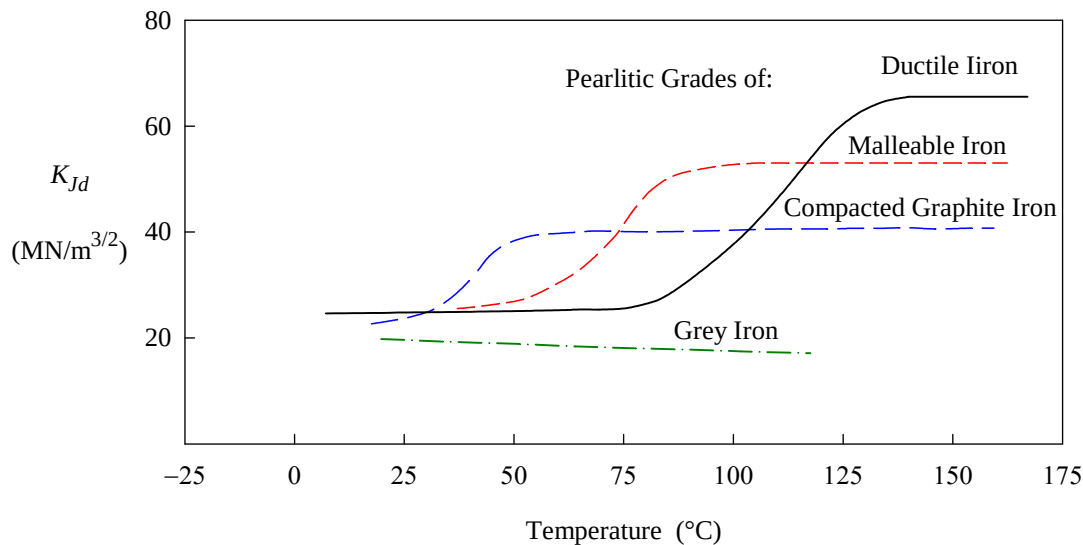


Sketch 3.2 Variation of fracture toughness with pearlite/ferrite content for grey cast iron at room temperature (Reference 31)



Sketch 3.3 Effect of graphite morphology on the dynamic fracture toughness of ferritic grades of cast irons as a function of temperature (Derivation 19)*

* Raw data not available.



Sketch 3.4 Effect of graphite morphology on the dynamic fracture toughness of pearlitic grades of cast irons as a function of temperature (Derivation 19)*

A comparison of the range of static fracture toughness values in Sketches 3.1 and 3.2 with the variation of K_{Jd} in Sketches 3.3 and 3.4 suggests that loading rate does not have a significant effect on levels of fracture toughness.

The toughness properties of grey cast irons are particularly sensitive to the rate of cooling experienced during the casting process. Coarser graphite flakes and a softer matrix structure form in thicker castings as a result of slower solidification and cooling, reducing the strength, and hence toughness, of the iron. This effect can be observed in Sketch 3.5. For each treatment of the material in question, toughness decreases with increasing thickness of the cast section.

3.1.1 Chilled cast iron

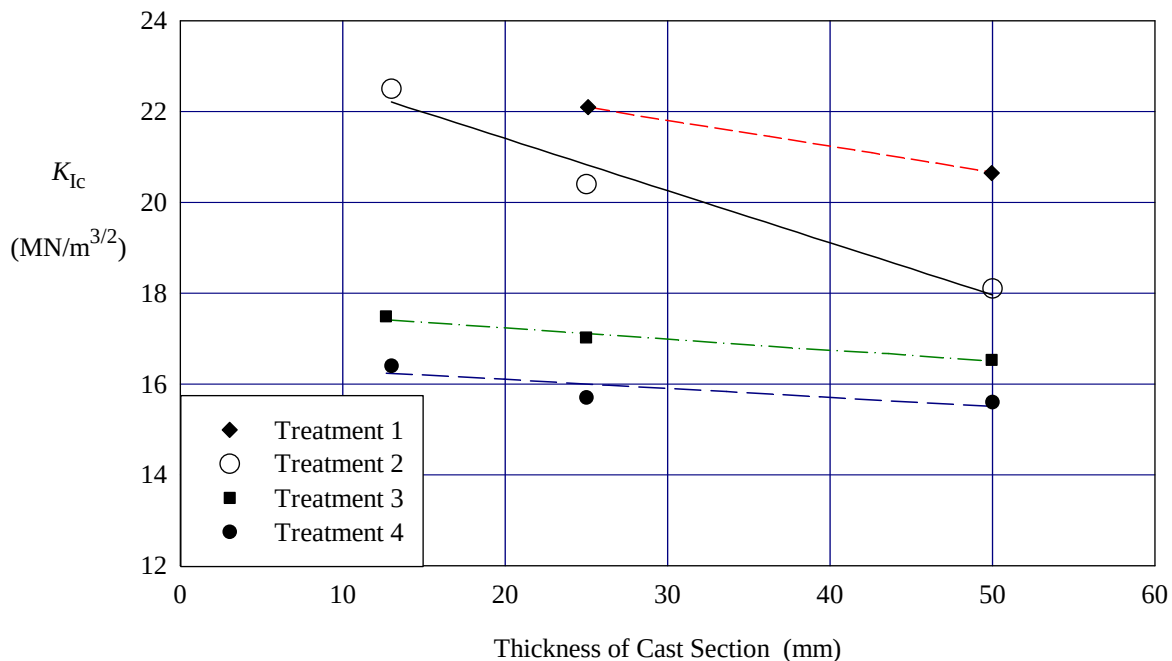
Chilled cast iron refers to cast iron formed from a process where grey cast iron is locally cooled very rapidly from the melt, leading to the formation of white cast iron in the region where cooling is applied (see Section 3.2 for an explanation of the fracture properties of white cast iron). The material properties vary with the intensity of chilling and distance from the location where the chill was placed. Other forms of cast iron may also be chilled.

Hypo-eutectic irons (Carbon Equivalent[†] < 4.3 per cent) cast in permanent moulds tend to experience a chill effect, and require heat treatment before use. Such castings are then referred to as 'chill-free'.

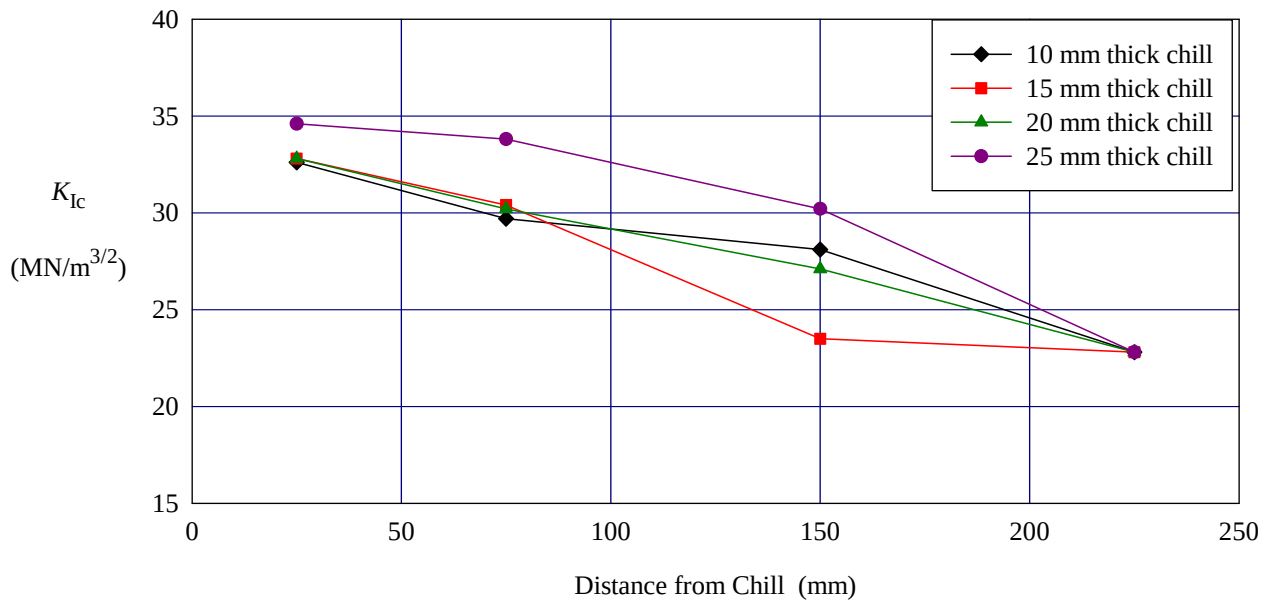
In Sketch 3.6, a variation of fracture toughness with distance from the chill is illustrated for a chilled cast iron. The data in this sketch relate to distances greater than 25 mm from the chill, and it can be seen that measured values of K_{Ic} fall with increasing distance. This is the result of a higher pearlite content in specimens that were machined from regions that were further from the chill.

* Raw data not available.

† Carbon Equivalent = Per cent Carbon + 1/3 x (per cent Silicon).

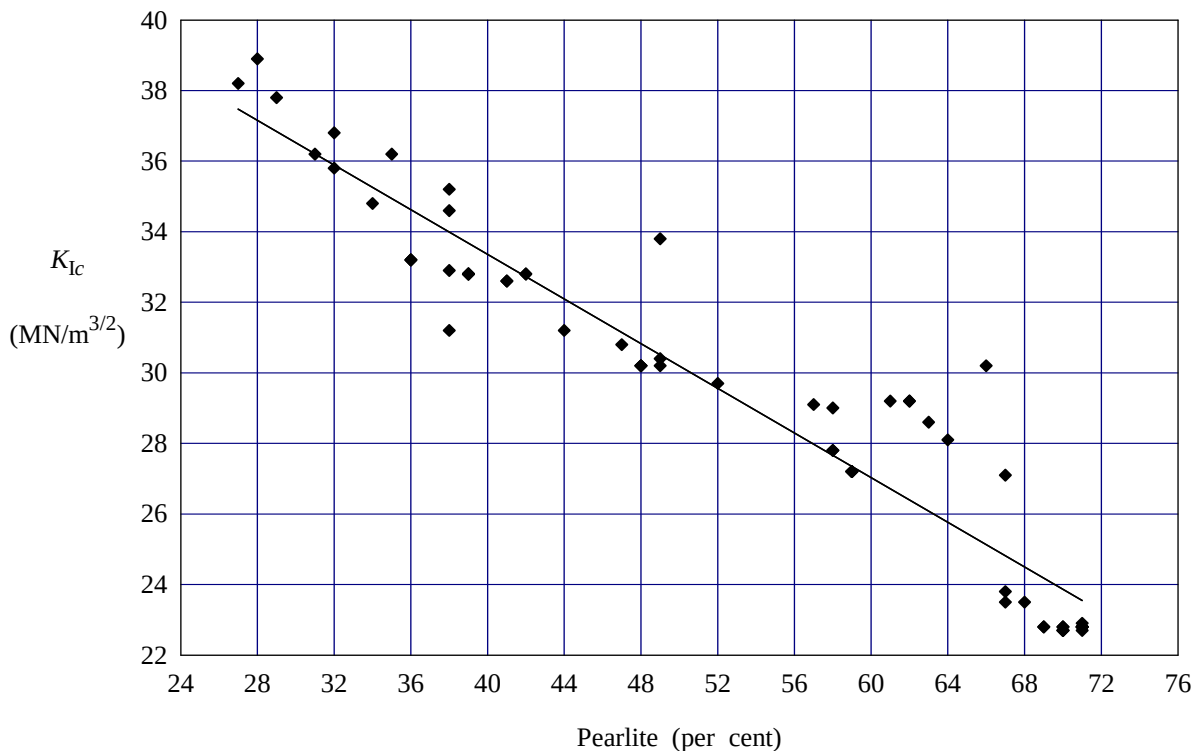


Sketch 3.5 Variation of fracture toughness of grey cast iron with thickness of cast section (Data used to construct Table 8.1.1)



Sketch 3.6 Fracture toughness versus distance from chill for a chilled cast iron at room temperature (Data used in construction of Table 8.2.1)

Sketch 3.7 shows a plot of fracture toughness versus pearlite content for chilled cast iron. It is expected that a very brittle casing of white cast iron would have formed at the surface of this material, where the chill was applied (K_{Ic} data at distances of less than 25 mm from the chill were not available). Hence the fracture toughness in the vicinity of the chill would be relatively low, with an initial increase with distance from the chill.



Sketch 3.7 Fracture toughness versus pearlite content for a chilled cast iron at room temperature (Derivation 24)

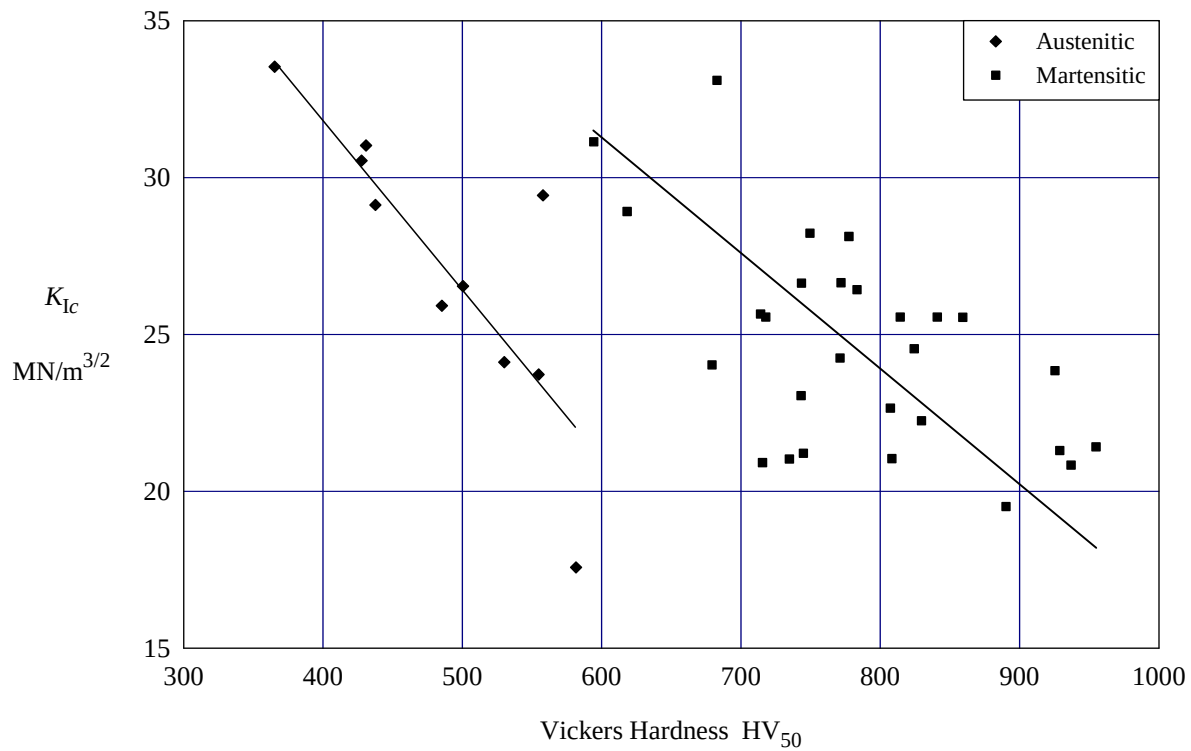
3.2 White Cast Iron

White cast iron includes a pronounced carbide phase (having a white crystalline structure), brought about by rapid cooling rates, which results in a hard, abrasion-resistant alloy. Fracture toughness values for white cast irons are generally low, with typical values in the region of 20 to 30 MN/m^{3/2} (18×10^3 to 27×10^3 lbf/in^{3/2}) (however, some experimental variants have approached 40 MN/m^{3/2} (36×10^3 lbf/in^{3/2})). Sketches 3.8 to 3.11 give an indication of the variation of toughness with hardness for various white cast irons.

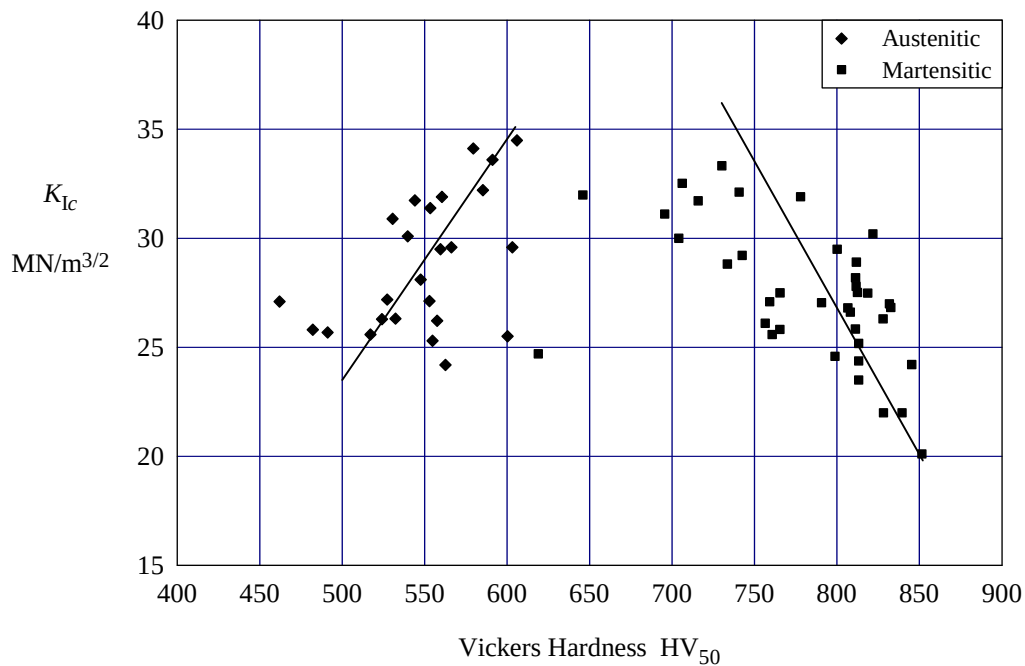
For a given microstructure, the toughness of white cast irons generally decreases with an increase in material hardness, see Sketches 3.8 to 3.10.

A martensitic structure results from carbon being trapped within the matrix leading to deformation of the grain structure. This leads to a high level of constraint within the structure, thus restricting dislocation movement. The material becomes harder because less deformation can take place owing to the constraint. Lower deformation of the material means that less energy can be absorbed at the crack tip. Hence crack propagation is easier (that is, fracture toughness is lowered).

A contrary trend of K_{Ic} increasing with hardness is observed for the Class IID austenitic white cast iron data, see Sketch 3.9. This may be the result of a lack of K_{Ic} data for such materials at lower hardness levels. An alternative explanation relates to the effect of fine carbide precipitates in the austenitic structure. These precipitates restrict dislocation movement and hence increase the material hardness (that is, the material becomes more brittle).



Sketch 3.8 Variation of fracture toughness with hardness for Class IIB white cast iron at room temperature (Data used to construct Tables 8.3.5 to 8.3.8 and 8.3.19 to 8.3.24)

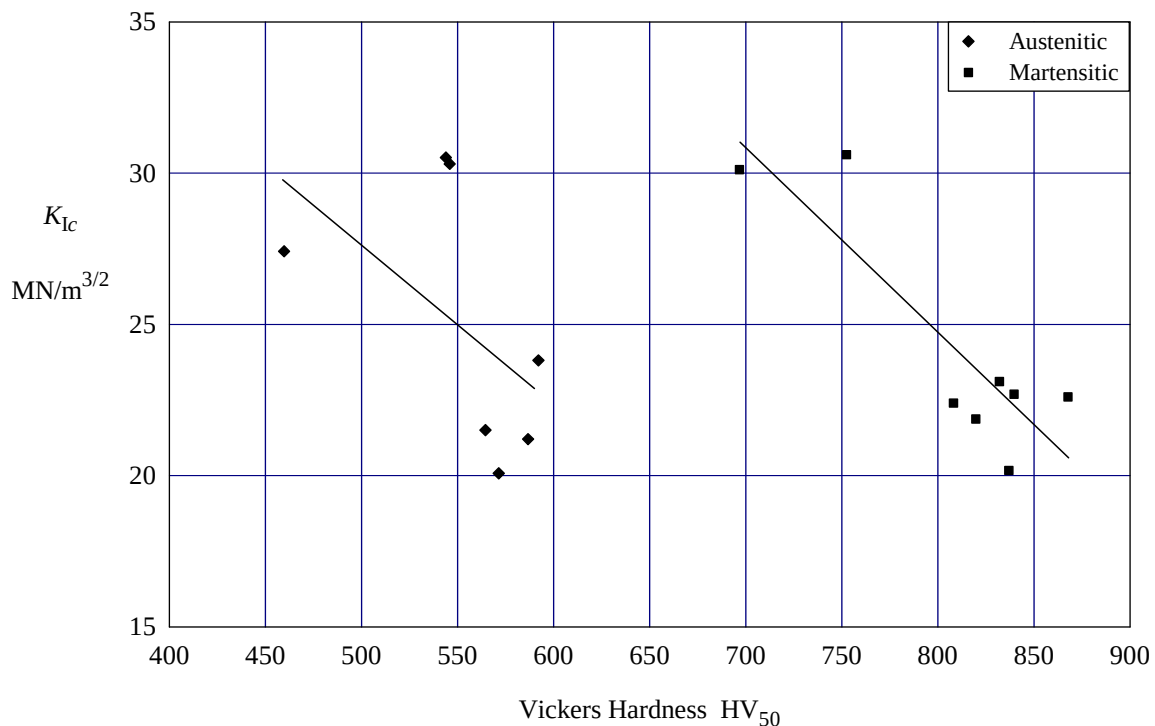


Sketch 3.9 Variation of fracture toughness with hardness for Class IID white cast iron at room temperature (Data used to construct Tables 8.3.9 to 8.3.14 and 8.3.25 to 8.3.29)

However, it should be pointed out that the tendency of K_{Ic} to increase with hardness is strongly influenced by the contribution from the data for one particular material (19Cr Austenitic White Cast Iron, Table 8.3.13). The material composition for each of these test specimens was closely controlled, and toughness/hardness was varied by different heat treatment procedures.

The reverse trend, that is, K_{Ic} decreasing with an increase in hardness, was noted in instances where the carbon content of certain white cast irons was increased, whilst the composition of the other elements was kept near-constant and the same heat treatment was applied to each specification (see 17Cr-1.5Mo-1Cu Austenitic and Martensitic White Cast Irons, Tables 8.3.7 and 8.3.23 respectively).

The Class IIIA austenitic white cast irons (Sketch 3.10) consist of two types of material. The 25Cr grade (Table 8.3.15) has a significantly higher carbon content than the 27Cr grade (Table 8.3.16) leading to considerably lower K_{Ic} values. To some extent a similar trend can be seen for the Class IIIA Martensitic White Cast Irons (Tables 8.3.30 and 8.3.31).

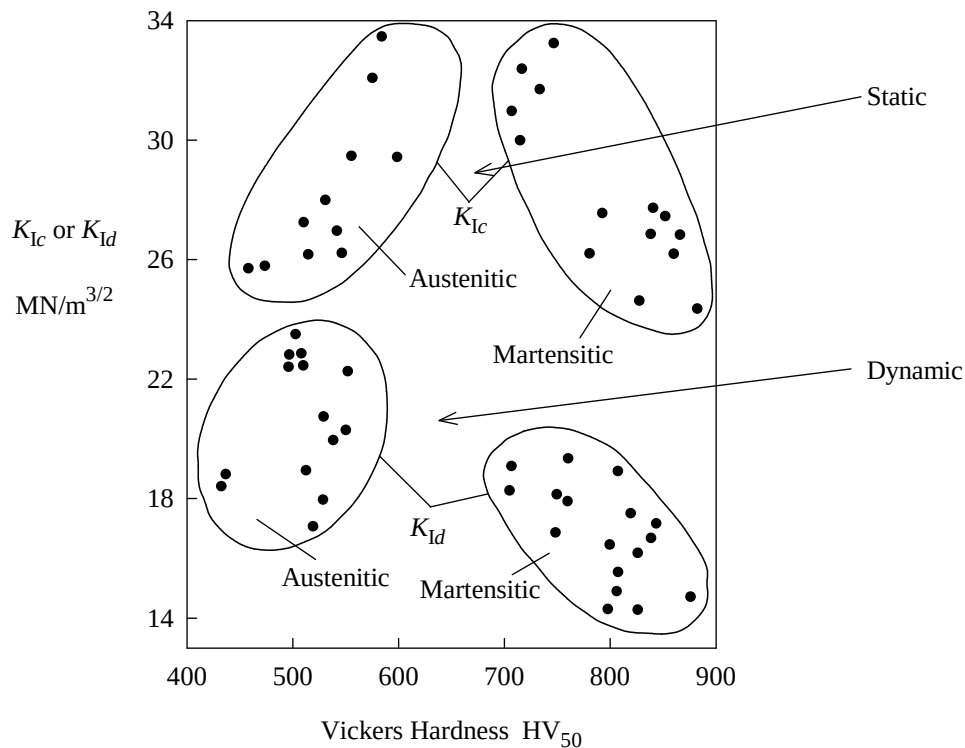


Sketch 3.10 Variation of fracture toughness with hardness for Class IIIA white cast iron at room temperature (Data used to construct Tables 8.3.15, 8.3.16, 8.3.30 and 8.3.31)

Some of the white cast iron fracture toughness data included were obtained from non-standard test specimens, and those data are indicated in the appropriate tables. Researchers chose alternative specimens in some instances owing to the difficulty in machining white cast iron with conventional tools.

There are no data available on the transition temperature of white cast iron. It is believed that any such transition would occur at very high temperatures, well beyond the bounds of any practical applications (Reference 41).

Testing of heat treated white cast irons suggests that a martensitic heat treatment has no significant effect on the static fracture toughness, compared with austenitic white iron. In dynamic testing, martensitic white cast irons appear to be inferior, see Sketch 3.11.



Sketch 3.11 Comparison between static (K_{Ic}) and dynamic (K_{Id}) fracture toughness of white cast iron with austenitic and martensitic microstructures for varying levels of hardness at room temperature (Data from Tables 8.3.13 and 8.3.28, and Derivation 6)

Specifications for the white cast irons included are given in Appendix D. In the cases where the material microstructure was not specified, the alloys in question were grouped according to Table D2.3, which lists the typical hardness ranges for different types of matrices in high chromium (> 25 per cent Cr) white cast irons.

3.3 Malleable Cast Iron

Malleable cast iron is essentially tempered white cast iron. The graphite forms as irregular ‘pop corn’-shaped, globules during a post-solidification heat treatment. Such cast irons are generally considered to have the best low-temperature properties of any form of cast iron. However, by comparing the data in Tables 8.5.5 to 8.5.7 with those in Tables 8.4.1 and 8.4.2, it can be seen that, in some instances, ferritic ductile cast irons have superior fracture toughness properties to malleable irons below the transition region.

Malleable cast irons generally have a lower transition temperature than ferritic irons due to lower silicon levels. Pearlitic malleable irons tend to have higher transition temperatures than the ferritic grades, see Sketches 3.3 and 3.4.

Linear elastic fracture mechanics methods have been found to be inappropriate for malleable cast irons. Using K_Q and K_{max} values is considered to be inadvisable, elastic-plastic methods being deemed more suitable (Derivation 19). Early J_{Ic} testing of malleable cast irons produced results that have generally been shown to be inaccurate by a more recent variant of the standard J_{Ic} test procedure. All malleable cast iron fracture toughness data in this Data Item were obtained from tests conforming to the more recent standard. Appendix B gives a comparison between the results obtained using the original method and the values recalculated using the later variant of the procedure.

Specifications for the malleable irons included in the Item are given in Appendix D.

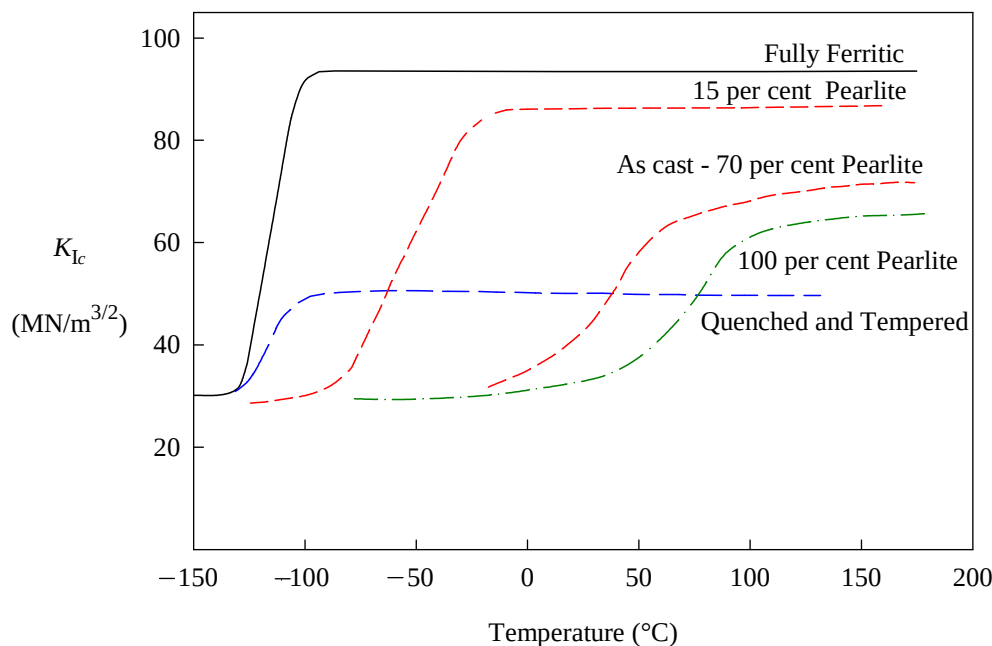
3.4 Ductile Cast Iron

Ductile cast iron (also called nodular cast iron or spheroidal graphite (SG) cast iron) includes graphite in the form of spherical globules to give the best toughness properties amongst the various types of cast iron.

Magnesium and/or cerium are added to the molten alloy to promote the formation of graphite. Selection of an appropriate inoculation procedure causes the graphite to form as nodules rather than flakes.

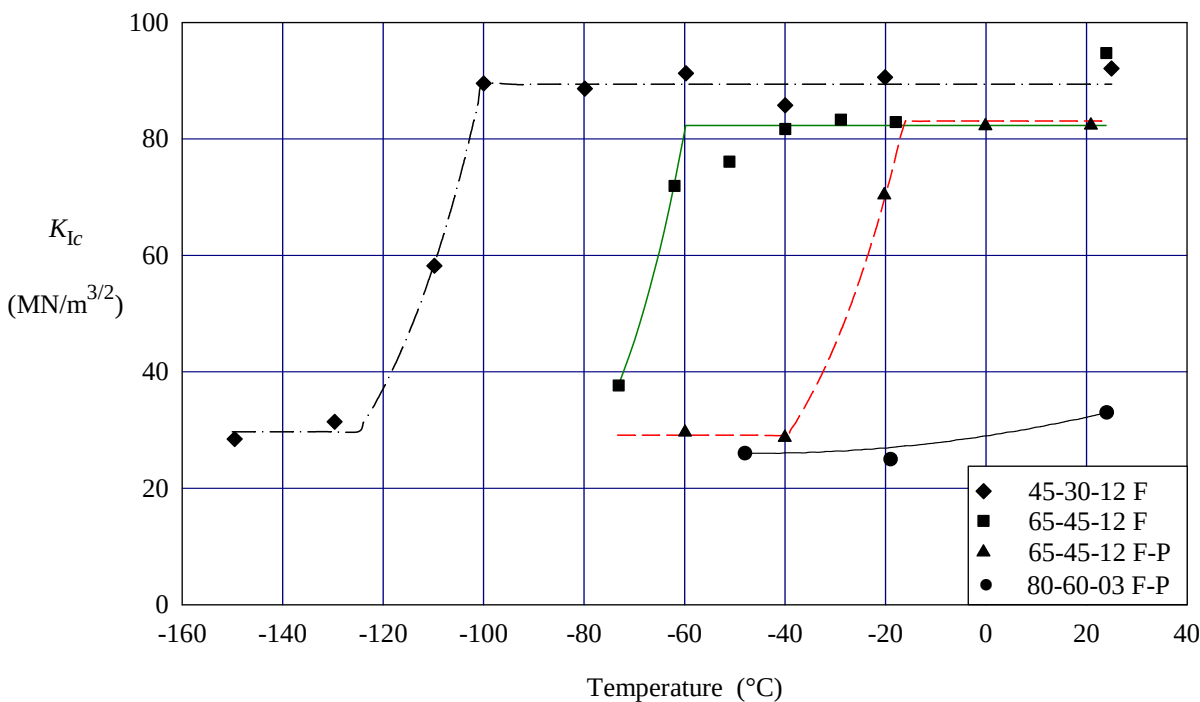
The fracture toughness of such irons has been shown to be dependent upon microstructure (ferritic or pearlitic), silicon content, degree of nodularity (percentage of globules with a nearly spherical shape), and the number of nodules per unit area (nodule count).

A typical room temperature fracture toughness value for a ferritic ductile iron is in the order of 80 to 90 $\text{MN/m}^{3/2}$ (73×10^3 to 82×10^3 $\text{lbf/in}^{3/2}$), although values in excess of 100 $\text{MN/m}^{3/2}$ (91×10^3 $\text{lbf/in}^{3/2}$) have been measured. Brittle-to-ductile transition temperatures are generally well below room temperature. A pearlitic microstructure has the effect of shifting the transition temperature upwards towards room temperature and above, and has a detrimental effect on the fracture toughness, in comparison with a ferritic microstructure, see Sketches 3.3, 3.4 and 3.12 to 3.14.

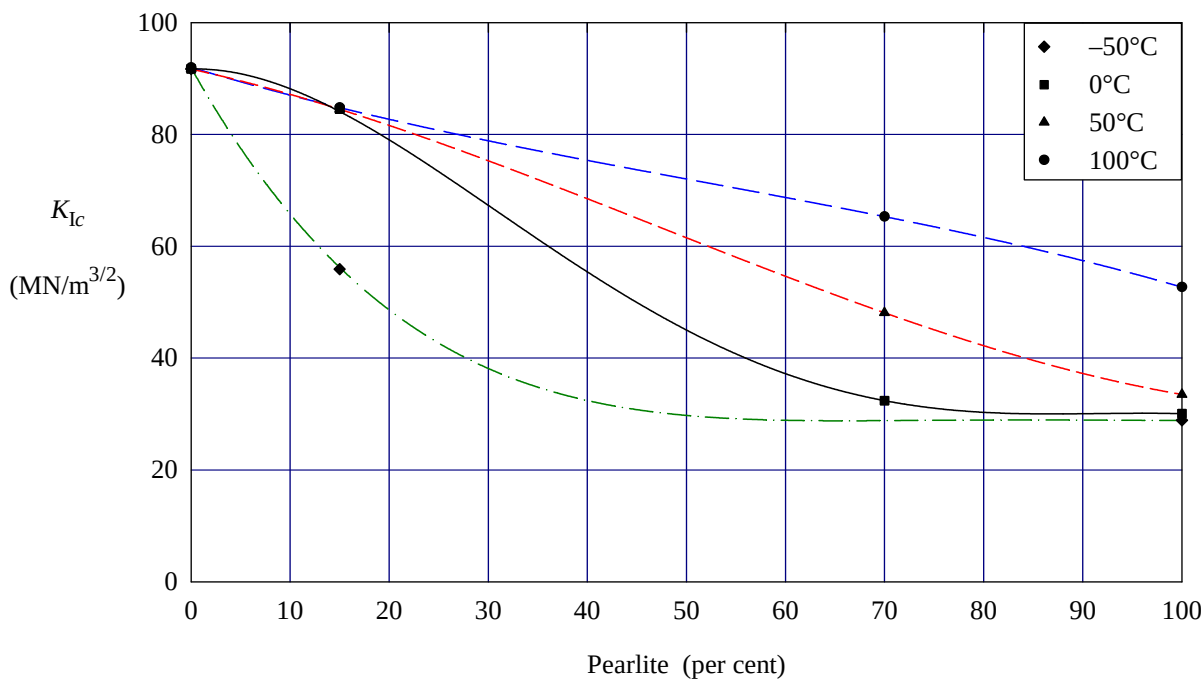


Sketch 3.12 Effect of microstructure on the fracture toughness of ductile iron as a function of temperature (Derivation 19)*

* Raw data not available.



Sketch 3.13 Comparison of fracture toughness as a function of temperature for a ferritic (F) and ferritic-pearlitic (F-P) ductile iron (Data from Tables 8.5.4, 8.5.5, 8.5.11 and 8.5.13)



Sketch 3.14 Effect of pearlite content on the fracture toughness of ductile iron (Derivation 19)*

* Raw data not available.

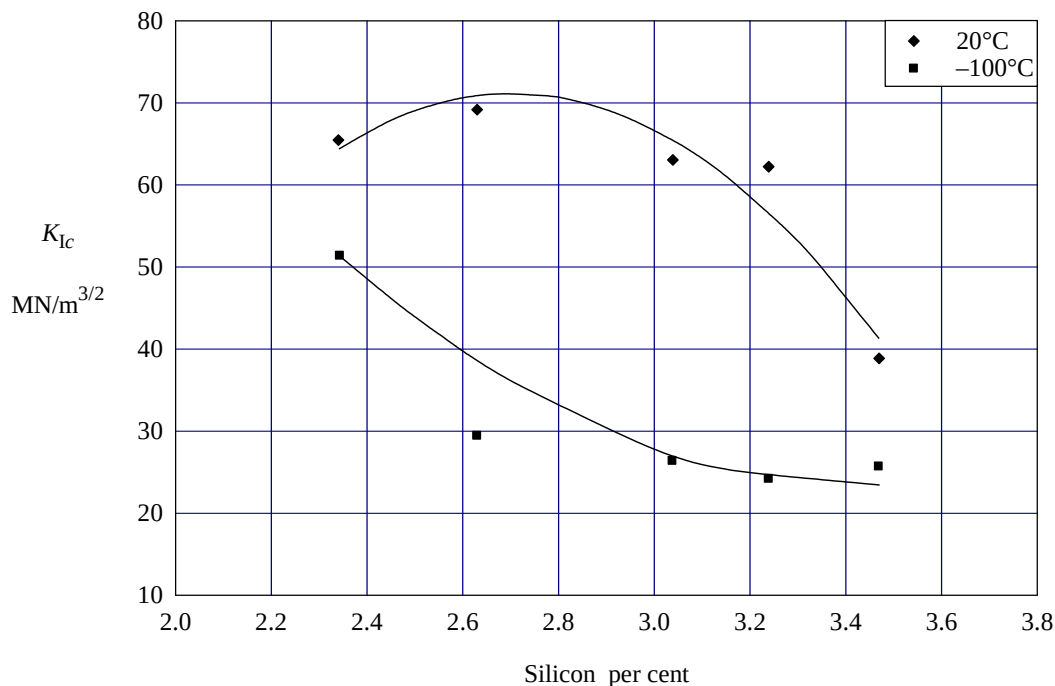
In many ductile irons, plane-strain conditions are only established at temperatures low enough to allow brittle fracture of the ferrite (often -100°C (-148°F) or lower), see Sketch 3.12. Valid K_{Ic} values generally cannot be obtained for temperatures greater than -40°C (-40°F) unless a very thick compact tension specimen is used. Therefore the J -integral method is often employed. (For example, a GGG-40 ductile cast iron, data for which are included in this Data Item (see Table 8.5.7), has a fracture toughness (measured from the J -integral) of $102.1 \text{ MN/m}^{3/2}$ ($92.9 \times 10^3 \text{ lbf/in}^{3/2}$) at room temperature, and a yield strength of 277 MN/m^2 ($40.2 \times 10^3 \text{ lbf/in}^2$). From Equation (2.1), a specimen of at least 340 mm (13.4 in) in thickness would be required to obtain a valid K_{Ic} measurement using LEFM techniques.)

Early elastic-plastic (J_{Ic}) measurements of the room temperature fracture toughness of **ferritic ductile cast irons** produced results that have been shown to be underestimates by a more recent variant of the standard J_{Ic} test procedure (Derivation 12). All ductile cast iron fracture toughness data calculated from the J -integral in this Data Item were obtained from tests conforming to the later method. Appendix B gives a comparison between certain results obtained using the original method and the values recalculated using the more recent procedure.

Quenching and tempering of ductile irons has an adverse effect on the upper-shelf fracture toughness, see Sketch 3.12.

An increase in silicon content can be detrimental to the fracture toughness of a ductile iron, even when the microstructure is predominantly ferritic, see Sketch 3.15.

Specifications for the ductile irons included in the Item are given in Appendix D.



Sketch 3.15 Fracture toughness versus silicon content for a ferritic ductile iron at 20°C (68°F) and -100°C (-148°F) (Data used to construct Table 8.5.9)

3.4.1 Compacted graphite cast iron

In **compacted graphite cast iron**, graphite forms as irregular rods, giving an anisotropic structure and properties. Ferritic grey iron forms on the surface of such materials, the result of a mould/metal reaction associated with sulphur pick-up during the casting process.

Little research has been conducted on the fracture toughness of such materials, though it could be argued that the properties lie between those of nodular and flake graphite (grey) irons, as the irregular graphite shape (referred to as 'vermicular') lies between the two. In an early study, the formation of vermicular graphite caused a 25 per cent reduction in the fracture toughness of as-cast ferritic specimens (Reference 32). A more recent study was unable to provide conclusive evidence that irregular graphite has a detrimental effect on fracture toughness, as a second variable, an increase in the pearlite content of the material, also played a role (see Derivation 8 and the data in Tables 8.5.20 and 8.5.21).

Compacted graphite irons have inferior upper-shelf properties compared to both ductile and malleable irons, but have a lower transition temperature, see Sketches 3.3 and 3.4. These observations apply to both ferritic and pearlitic microstructures, though the transition temperature is higher for the latter.

3.4.2 Factors influencing the fracture toughness of ductile and compacted graphite cast iron

The fracture toughness of ductile and compacted graphite cast iron is influenced by the following factors.

(a) Volume Fraction of Graphite

Experiments have shown that the upper-shelf toughness of nodular iron decreases as the volume fraction of graphite is increased. Maintaining a constant nodule count, whilst increasing the volume fraction of graphite has proved difficult to achieve. Hence there is uncertainty as to whether the observed reduction is an indirect result of the increased nodule count, or if increasing the graphite volume fraction whilst holding the nodule count constant (through increasing the nodule size) would have a similar effect.

(b) Nodule Count

Nodule count refers to the number of graphite nodules per unit area.

Research with Charpy and dynamic tear specimens has shown that a high nodule count (reduced internodular spacing) reduces the upper-shelf fracture toughness and lowers the brittle-to-ductile transition temperature of ductile irons, see Sketch 3.16.

This is believed to be the result of an increased number of nodules aiding void coalescence at the crack tip because the nodule spacing will be closer.

(c) Graphite Nodularity

The shape of graphite nodules has been demonstrated to have an effect on the upper-shelf fracture toughness of ductile cast iron.

The nodule shape (Sh) is given by the relationship:

$$Sh = 4\pi \frac{A}{U^2}, \quad (3.1)$$

where A = area of appropriate/typical cross-section of graphite nodule

and $U =$ circumference of appropriate/typical cross-section of graphite nodule.

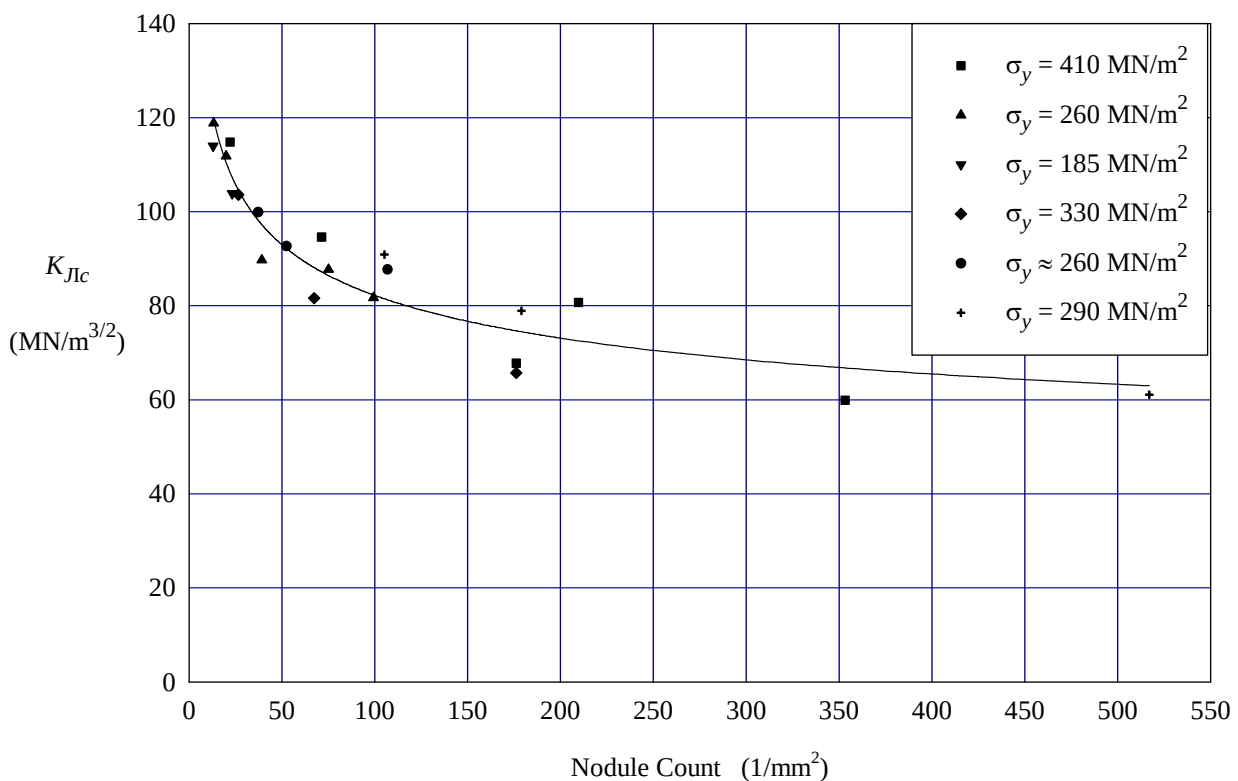
An Sh value of 1 indicates a perfectly spherical nodule.

The degree of nodularity indicates the percentage of nodules in a matrix with a nearly spherical shape.

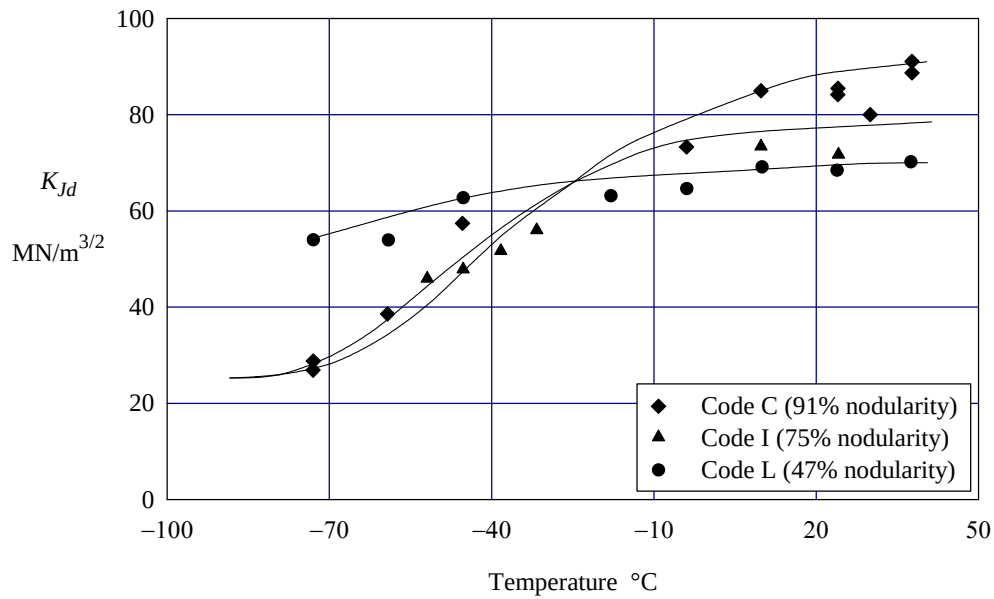
Alternatively, nodularity has also been defined as the percentage of nodules with an aspect ratio of less than 2 (Derivation 19).

In a particular study (Derivation 19), the upper-shelf fracture toughness of ferritic ductile iron was found to fall from around 90 to 70 $\text{MN/m}^{3/2}$ (82×10^3 to 64×10^3 $\text{lbf/in}^{3/2}$) as the degree of nodularity decreased from 91 to 47 per cent, see Sketch 3.17.

Nodularity is high for ductile irons, and low for compacted graphite irons.



Sketch 3.16 Effect of nodule count on the upper-shelf fracture toughness of ferritic ductile iron (Derivation 19)



Sketch 3.17 Effect of nodularity on the dynamic fracture toughness of ductile cast iron as a function of temperature (Derivation 19)

4. FACTORS AFFECTING FRACTURE TOUGHNESS

The following sections discuss the effect on fracture toughness of the most important factors that are often varied during a test programme to reflect service conditions. *In general, for a given class of material, any treatment that increases the proof stress is likely to reduce the fracture toughness. However, the reverse trend is observed for grey cast iron, see Sketch 3.1.*

4.1 Heat Treatment

The effects of heat treatment on the fracture toughness of cast irons tend to be specific to the type of cast iron and no generalisation is possible. However, there are some trends for certain classes of irons.

For example, the formation of a pearlitic microstructure (as opposed to ferritic) tends to lead to a lower fracture toughness in ductile irons, all other things being equal. An opposite trend has been observed for grey irons.

Chilled cast iron, a variant of grey iron, experiences a decrease in toughness with an increase in pearlite content.

Heat treating white cast iron to produce an austenitic, as opposed to martensitic, microstructure does not appear to have a significant effect on the static toughness. However, a lower dynamic toughness is observed for martensitic white cast irons, see Sketch 3.11. Similarly, the tempering of white cast iron to form malleable iron leads to a much higher fracture toughness.

4.2 Temperature

All of the data in this Item that show the dependence of fracture toughness on temperature, with the exception of the grey cast iron data in Sketches 3.3 and 3.4, are for malleable, ductile or compacted graphite cast irons.

Depending upon the alloy composition and microstructure, the temperature at the onset of the brittle-to-ductile transition region can vary from room temperature for a number of materials to less than -100°C (-148°F) for ductile cast irons, see Sketch 3.12.

4.3 Thickness

Metallurgical variations and a change in mechanical properties are often evident across thick sections. A result of this is that the measured fracture toughness of a cast iron section is likely to be affected by the thickness of the component from which the specimen is taken.

The influence of cast section thickness on toughness is particularly evident in grey cast iron, where the slower solidification and cooling of a thicker section results in the formation of coarser graphite flakes and a softer matrix structure thus reducing the strength, and hence toughness, of the iron. This is illustrated in Sketch 3.5, where the fracture toughness of a grey cast iron is shown to decrease with increasing cast section thickness.

Additionally, residual stresses are likely to be present in a large component. Therefore when producing a thick component from a particular material, the designer will need to estimate the actual stress intensity, either by compounding the stress intensities resulting from both the load applied to the component and the residual stresses in the region of interest, or by referencing appropriate literature on elastic-plastic fracture mechanics.

Testing has also demonstrated that the effect of test specimen thickness on the measured fracture toughness of a material can vary with temperature (see Derivation 20).

4.4 Orientation and Surface Effects

Cast alloys are often characterised as having a coarse two-phase microstructure (similar in concept to a composite material), which is generally a combination of brittle (low toughness) and ductile (high toughness) phases. For cast iron, the ductile phase is the matrix, and the brittle phase is the graphite. It should be noted that such a representation is only accurate on a local scale.

Components with cast surfaces tend to have inferior fracture resistance properties to those with machined surfaces. This has been demonstrated with ductile cast iron, where the roughness and micro-inclusion content of cast surfaces were shown to have deleterious effects. Shot blasting of components can also have a negative influence (Reference 40).

4.5 Environment

The data in this Item are from tests carried out in normal atmospheric conditions. Materials exposed to hydrogen, corrosive agents or nuclear irradiation will often have reduced fracture toughness. For example, under corrosive conditions cracks may be lengthened and subsequent failure will occur under static loads that are much lower than would normally cause brittle fracture in air.

4.6 Form of Test Specimen

The use of the three-point bend specimen, from which some of the fracture toughness values in this Data Item were obtained, is not recommended owing to complications introduced by the difference between the tensile and compressive moduli of elasticity of cast iron.

The use of such specimens has been shown to over-estimate the fracture toughness of a material, as is shown in Sketch 4.1, which compares the fracture toughness measured with single-edge notched bend (SENB) and single-edge notched tension (SENT) specimens. In each instance, the fracture toughness of the SENB specimen is approximately 20 per cent higher.

Therefore when using fracture toughness data obtained from three-point bend specimens, the designer will need to account for the possible over-prediction in K_{Ic} .

4.7 Rate of Loading

4.7.1 Static testing

The data relating to static fracture toughness in this Item cannot be applied with confidence to rates of loading that are significantly different from those implied by the rate of increase of stress intensity specified in the standard test procedures, that is 0.55 to $2.75 \text{ MN}/(\text{m}^{3/2}\text{s})$ (500 to $2500 \text{ lbf}/(\text{in}^{3/2}\text{s})$). This precludes, for example, impact loading.

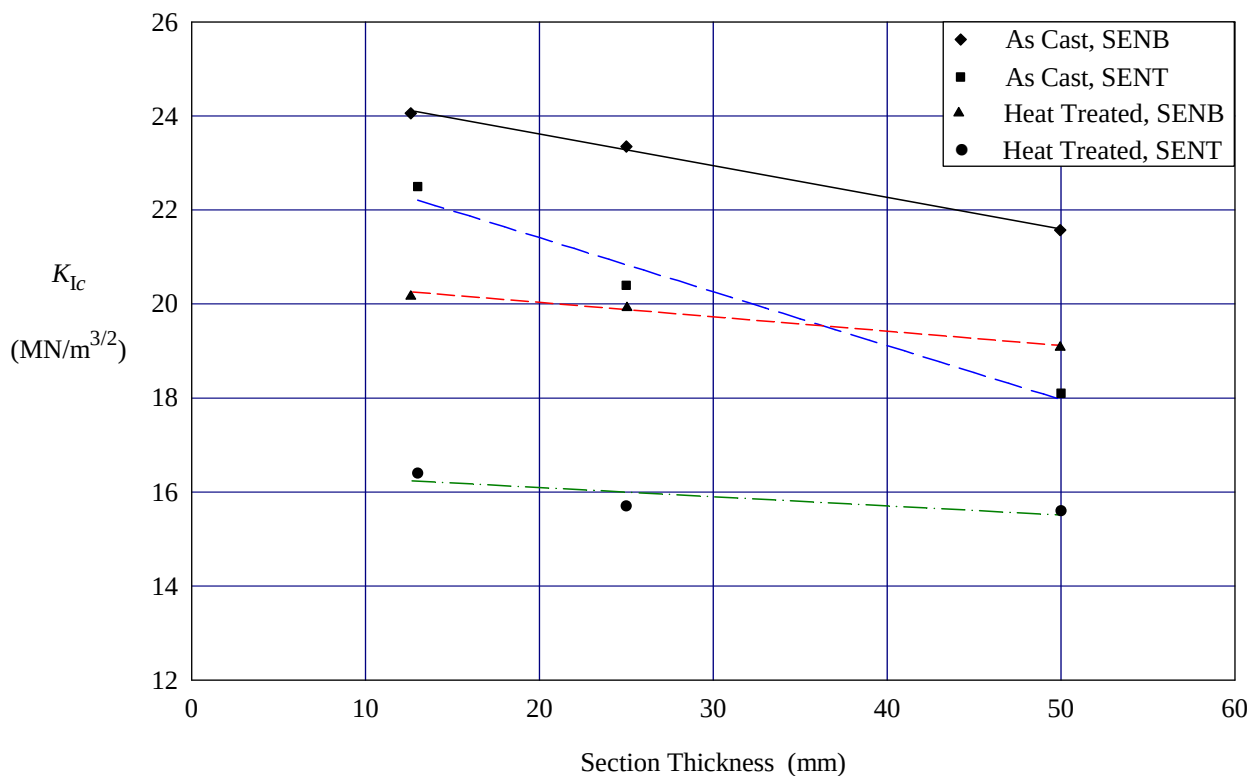
4.7.2 Dynamic testing

The dynamic data included in this Item, unless noted, conform to the requirements of the rapid load plane-strain fracture toughness provision in Reference 37. This procedure relates to testing at a rate of increase in stress intensity in excess of $2.75 \text{ MN}/(\text{m}^{3/2}\text{s})$ ($2500 \text{ lbf}/(\text{in}^{3/2}\text{s})$).

There has been limited testing of the dynamic fracture toughness of cast irons, but research suggests that

dynamic testing results in lower values of toughness for white cast iron, see Sketch 3.11 However, for ferritic ductile iron the rate of increase of stress intensity appears to have a negligible effect on toughness values in the upper-shelf region (Derivation 18).

Many of the dynamic fracture toughness data available for nodular cast iron have been obtained using specimens other than those recommended in Reference 37. Such results have not been included in this Data Item. Charpy V-notch and dynamic tear specimens have generally been deemed to be inappropriate for fracture toughness measurements of ductile irons, whilst the use of fatigue pre-cracked Charpy specimens to obtain fracture toughness values is only considered to be suitable for ferritic ductile iron (Derivation 19).



Sketch 4.1 Comparison of fracture toughness values of a grey cast iron measured with single-edge notched tension (SENT) and single-edge notched bend (SENB) specimens (Derivation 3)

5. STATISTICAL ANALYSIS OF DATA

5.1 Introduction

This section presents the results of statistical analyses to provide K_{Ic} values for particular materials, which the designer may use with a prescribed level of confidence. The derived quantities assume a specified probability of survival, and so may be considered to include a factor to account for material variability.

The individual fracture toughness values calculated are referred to as *Design Allowable* K_{Ic} values.

Two separate techniques have been employed to enable a *Design Allowable* K_{Ic} to be determined; they are referred to in this Item as the Regression Analysis Method (see Section 5.2) and the Group Analysis Method (see Section 5.3).

With the Regression Analysis Method a curve of mean K_{Ic} (or K_{Id}) versus a known material property is produced (the Regression Curve), whilst with the Group Analysis Method a mean fracture toughness value is determined ($(K_{Ic})_{mean}$ or $(K_{Id})_{mean}$). To determine the design allowable, a 99 per cent probability of survival was assumed with a 95 per cent level of confidence (that is, 99 per cent of K_{Ic} measurements for a particular material investigated will be greater than the *Design Allowable* K_{Ic} quoted with a 95 per cent level of confidence).

For an explanation of the term confidence level, see ESDU 91041, Section 1.6.

Design Allowable K_{Ic} values may be obtained from Figures 1 to 10, and 12, of Section 5.2 and from Tables 5.2, 5.3a and 5.3b of Section 5.3. Guidance on which of those sources to use is given in Section 5.1.1.

5.1.1 Guidance on selection of *Design Allowable* K_{Ic}

The Regression Analysis Method, which involves relating the fracture toughness of a material to a particular parameter (for example, hardness), could only be applied to the materials represented by Figures 1 to 12 of Section 5.2, owing to a lack of data for the other materials.

Corresponding *Design Allowable* K_{Ic} values were calculated for Figures 1 to 9, and for particular regions of the curves in Figures 10 and 12.

If the designer is concerned with one of the materials represented by these figures, and has knowledge of the relevant correlation parameter, then the technique should prove to be more accurate than the Group Analysis Method.

Instances may arise where, although the material under consideration is not included in Figures 1 to 9, or 10 and 12, it is similar in terms of chemical composition, microstructure or properties to one of the materials represented in those figures. In such cases, the general trends shown in those figures (for example, the ratio of the *Design Allowable* K_{Ic} to the mean K_{Ic}) will provide some useful guidance.

The Group Analysis Method has been applied to the majority of the irons for which data are presented in Section 8 (it follows the procedure employed in earlier Items on the fracture toughness of engineering materials, which draws on the techniques in ESDU 91041). However, in general there were an insufficient number of test samples to perform a rigorous statistical analysis for the individual material specifications. Furthermore, a number of approximations were employed (see Appendix F, Section F3). Consequently, the scatter within the various groups tends to exceed that of their constituent materials. Ignoring the effect of other parameters on fracture toughness (that is, assuming that K_{Ic} is constant regardless of the magnitude of such variables) contributes to scatter. Hence it is likely that in some instances this *Design Allowable* K_{Ic} will be excessively conservative. (For example, a *Design Allowable* K_{Ic} of 12.6 MN/m^{3/2} (11.5 × 10³ lbf/in^{3/2}) was determined for Class IIB White Cast Irons using the Group Analysis Method (Table 5.2 in Section 5.3). However, Figures 4 and 5 in Section 5.2, which illustrate the relationship

between K_{Ic} and hardness for this material, show that the *Design Allowable* K_{Ic} values predicted by the Regression Analysis Method are considerably greater over a significant portion of the hardness range considered.)

Additionally a number of the material groups formed for the Group Analysis Method studies failed the Normality test conducted.

For instances where the design application is critical, selecting the more conservative value of the *Design Allowable* K_{Ic} (which is generally produced by the Group Analysis Method of Section 5.3) might be deemed preferable.

When designers have their own fracture toughness data and related values of one or more of the parameters that influence toughness, the Regression Analysis Method is likely to be more appropriate for determining *Design Allowable* K_{Ic} values. When only fracture toughness values are available, this procedure cannot be employed, and the Group Analysis Method might be of use.

If the user is concerned with a material not covered by the tables in Sections 8 and 9, the use of relationships or quantities derived for materials with similar specifications and/or properties in Sections 5.2 or 5.3 may be deemed appropriate.

5.2 Regression Analysis Method

5.2.1 General notes on regression analysis

In the sketches in Section 3 of this Item, relationships can be observed between the fracture toughness of cast iron and other material properties or parameters.

A summary of such correlations is given in Table 5.1.

The objective of the Regression Analysis Method is to determine a function (the 'Regression Curve' equation) which relates the K_{Ic} (or K_{Id}) of a material to a particular parameter (for example, hardness), and subsequently to predict the *Design Allowable* K_{Ic} (or *Design Allowable* K_{Id}) for a given value of this property/condition.

Figures 1 to 9 (Section 5.2.3) provide regression curves and corresponding *Design Allowable* K_{Ic} values (which assume a 99 per cent probability of survival based on a 95 per cent level of confidence) for the relationships observed between the fracture toughness values of cast iron and other parameters (as listed in Table 5.1).

Relationships between fracture toughness and temperature for various ductile irons are provided in Figures 10 to 12. Design allowables are included in some instances.

Users should refer to Appendix E, Section E4 if they wish to utilise alternative criteria to determine design allowable values.

Unless noted otherwise, the regression functions are significant at the 5 per cent level.

For the analysis, only data that were directly available were considered. For example, if a sample size of five was quoted for the K_{Ic} of a particular material, but the individual test data were not available, only one value was considered.

Any outlier values observed in the data were excluded from the analyses, as such values were inconsistent with the general trends predicted by the corresponding models. The inclusion of such values has the effect of producing a non-Normal error distribution, hence invalidating any relationships developed.

A linear regression analysis procedure was followed in all cases, with the exception of the ductile irons.

The relationships and procedures employed for the Regression Analysis Method are outlined in Appendix E. The relevant theory was obtained from References 42 and 43.

5.2.2 Ductile iron analyses

The data available for ductile irons demonstrated a correlation between fracture toughness and test temperature.

A typical K_{Ic} versus T curve for ductile iron comprises a lower shelf (minimum toughness), where toughness is constant with respect to temperature, a transition region, where toughness increases with temperature, and an upper shelf (maximum toughness), where fracture toughness does not vary with temperature (see Sketch 5.1).

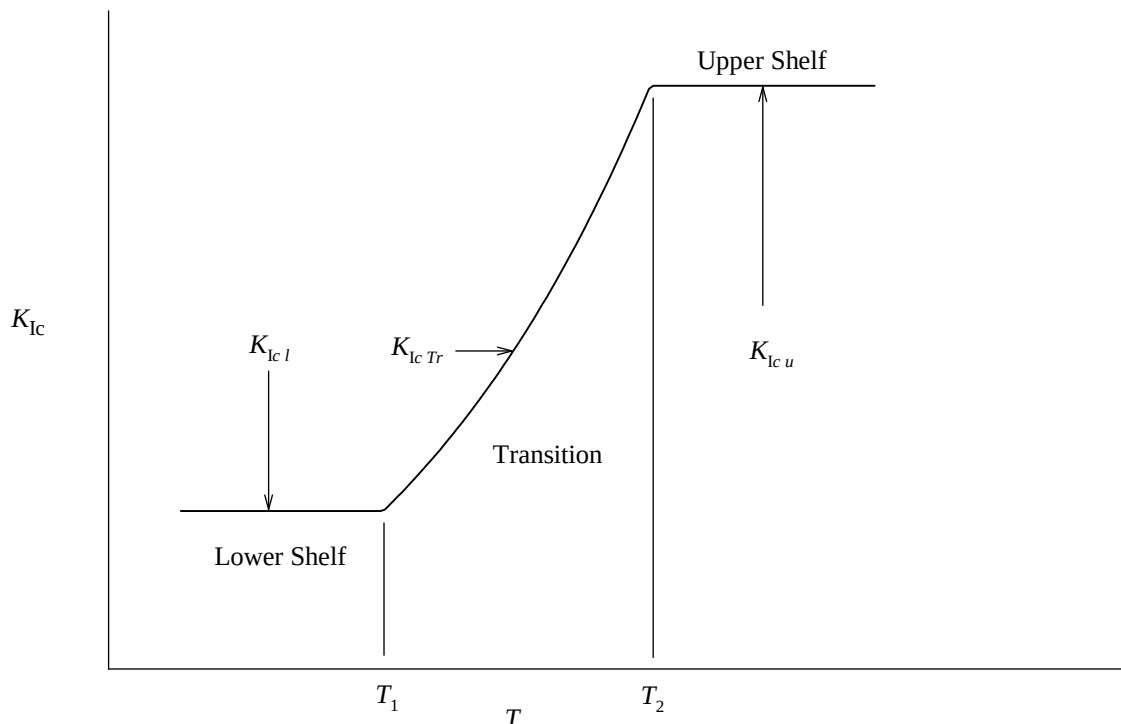
The parameters involved are:

$K_{Ic l}$	lower-shelf fracture toughness,
$K_{Ic u}$	upper-shelf fracture toughness,
$K_{Ic Tr}$	transition region fracture toughness,
T_1	temperature at which transition region commences and
T_2	temperature at which transition region concludes.

For dynamic fracture toughness, the 'c' subscript is replaced with a 'd'.

The objective of the regression analyses for ductile irons was to produce a set of curves that modelled the three distinct regions (the 'Three-Curve Method'). A logarithmic fit was used in the transition region, with constant values of K_{Ic} assumed for the upper and lower shelves.

Figures 10 to 12 of Section 5.2.3 represent some of the ductile iron data sets.



Sketch 5.1 Brittle-to-ductile transition curve

TABLE 5.1 Forms of Cast Iron and their Related Parameters[†]

Material	Related Parameter	Figure	Data in Table(s)
Grey Cast Iron	Brinell hardness, HB	1	8.1.1, 8.1.2
Grey Cast Iron	Tensile strength, σ_{uts}	2	8.1.1-8.1.3
Chilled Cast Iron	Per cent pearlite, P	3	8.2.1
Class IIB Austenitic White Cast Iron	Vickers hardness, HV ₅₀	4	8.3.5-8.3.8
Class IIB Martensitic White Cast Iron	Vickers hardness, HV ₅₀	5	8.3.19-8.3.24
Class IID Austenitic White Cast Iron	Vickers hardness, HV ₅₀	6	8.3.9-8.3.14
Class IID Martensitic White Cast Iron	Vickers hardness, HV ₅₀	7	8.3.25-8.3.29
Class IIIA White Cast Iron	Vickers hardness, HV ₅₀	8	8.3.15, 8.3.16, 8.3.30, 8.3.31
White Cast Iron	Vickers hardness, HV ₅₀	9	8.3.1-8.3.36
GGG-35.3 Ferritic Ductile Iron	Temperature, T	10	8.5.6
GGG-35.3 Ferritic Ductile Iron (Dynamic Fracture Toughness)	Temperature, T	11	9.1.3
GGG-40 Ferritic Ductile Iron	Temperature, T	12	8.5.7

[†] Tables E5.1 and E6.1 of Appendix E list the location of the tables presenting the Regression Analysis Method parameters.

5.2.2.1 Normalising test data to construct fracture toughness versus temperature curves

Owing to the high degree of scatter that is associated with collating test data from various sources, a normalising procedure was applied to the temperature values of the individual data sets.

The procedure is outlined in Appendix E, Section E3.3.

Before reading a value of fracture toughness off the appropriate figure, it is necessary for the user to subtract the corresponding temperature translation parameter value, ΔT , for the relevant specification from the temperature of interest (see Appendix E, Section E3.3).

The technique was not applied to the data in Figure 11 (K_{Id} versus T for GGG-35.3) as all of the measurements were taken from the same source in this instance. Thus the degree of variability is relatively low.

5.2.2.2 Notes on Design Allowable K_{Ic} and K_{Id} curves

Design allowable values were not calculated in the transition region for any of the materials considered owing to the wide degree of scatter and uncertainty associated with the region.

The lack of test data in the lower-shelf region for GGG-35.3 ferritic ductile iron (see Figure 10) prevented *Design Allowable* K_{Ic} values from being calculated in this zone.

For similar reasons, *Design Allowable* K_{Id} values could not be determined in any region for the dynamic fracture toughness of this material (see Figure 11).

5.2.3 Figures

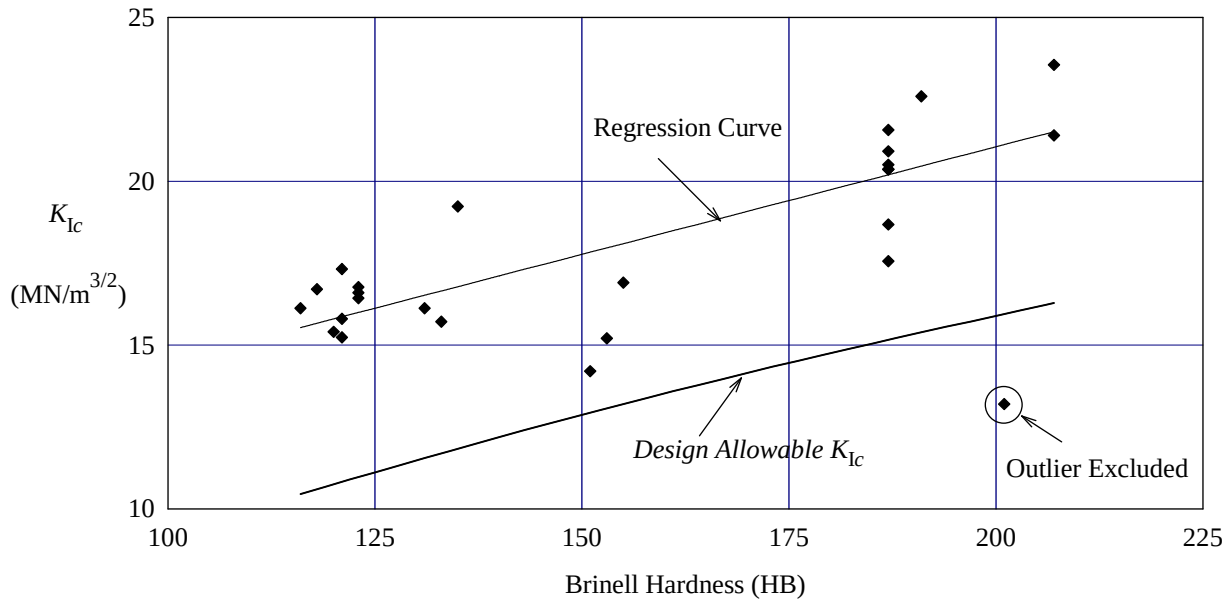


FIGURE 1 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HB) FOR GREY CAST IRON (Data used to construct Tables 8.1.1 and 8.1.2*)

* Raw data not available in all instances.

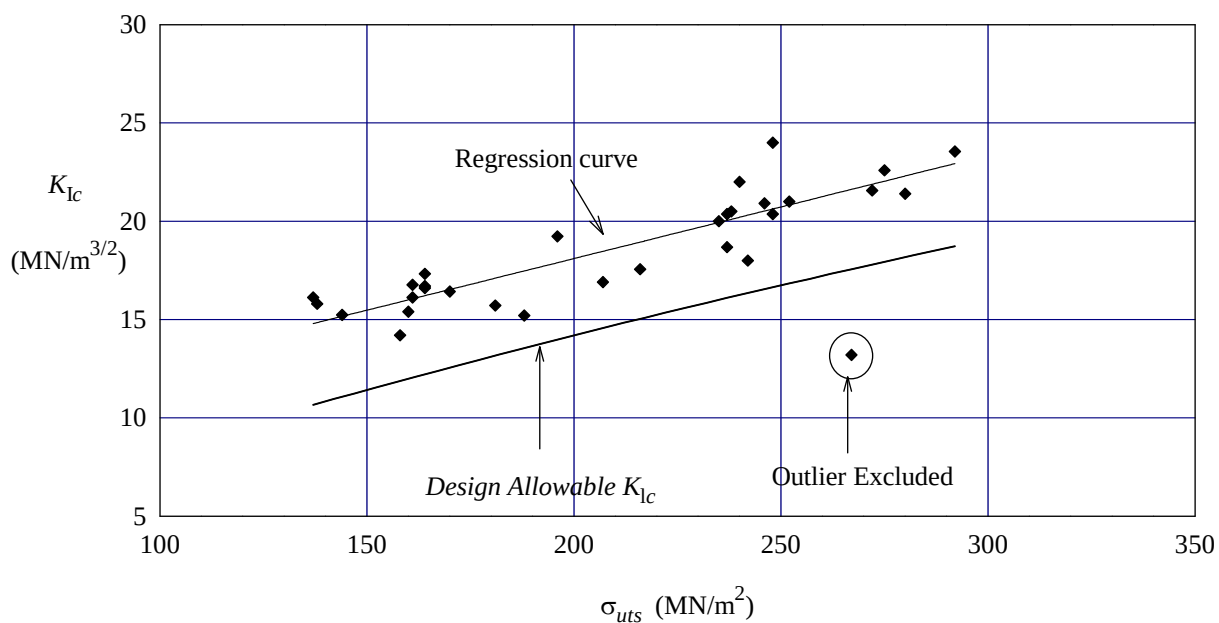


FIGURE 2 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND σ_{uts} FOR GREY CAST IRON (Data used to construct Tables 8.1.1 to 8.1.3*)

* Raw data not available in all instances.

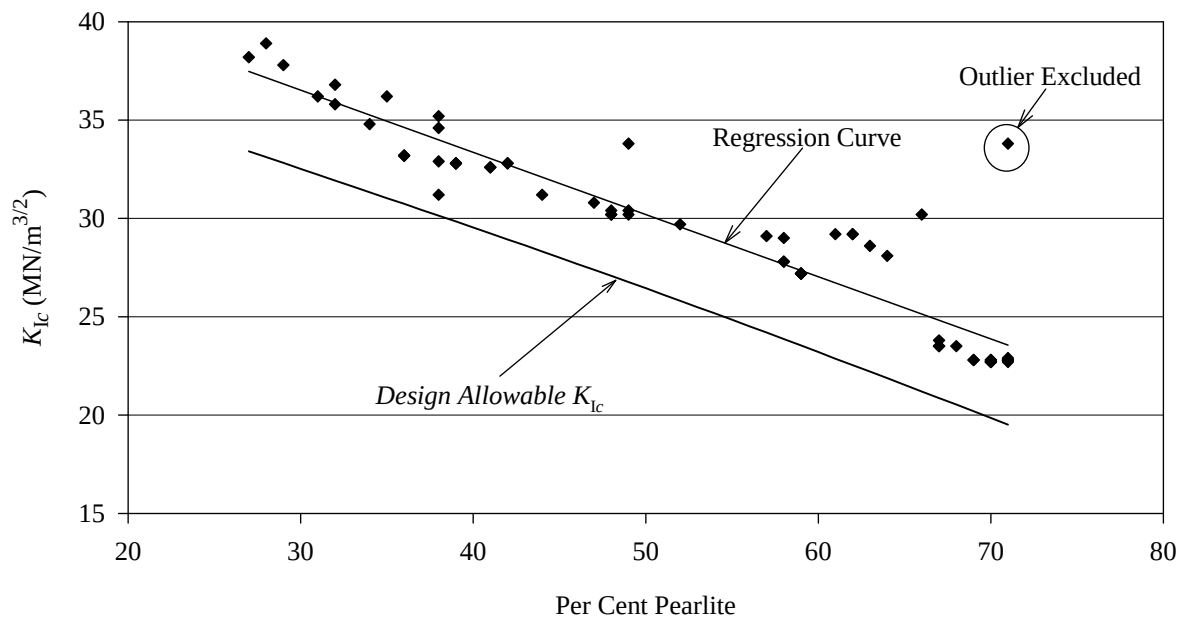


FIGURE 3 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND PERCENTAGE PEARLITE FOR CHILLED CAST IRON (Raw data used to construct Table 8.2.1. See Table 8.2.2 for data relating fracture toughness to percentage pearlite content)

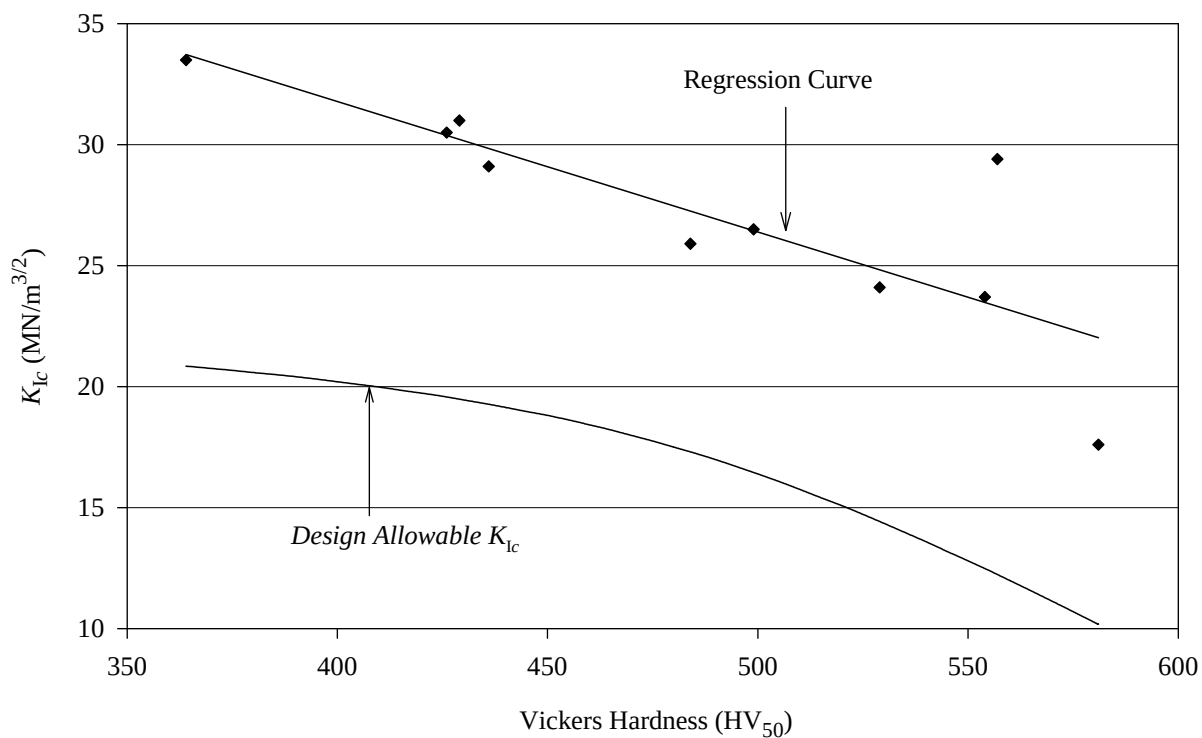


FIGURE 4 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HV_{50}) FOR CLASS IIB AUSTENITIC WHITE CAST IRON (Data used to construct Tables 8.3.5 to 8.3.8*)

* Raw data not available in any instances.

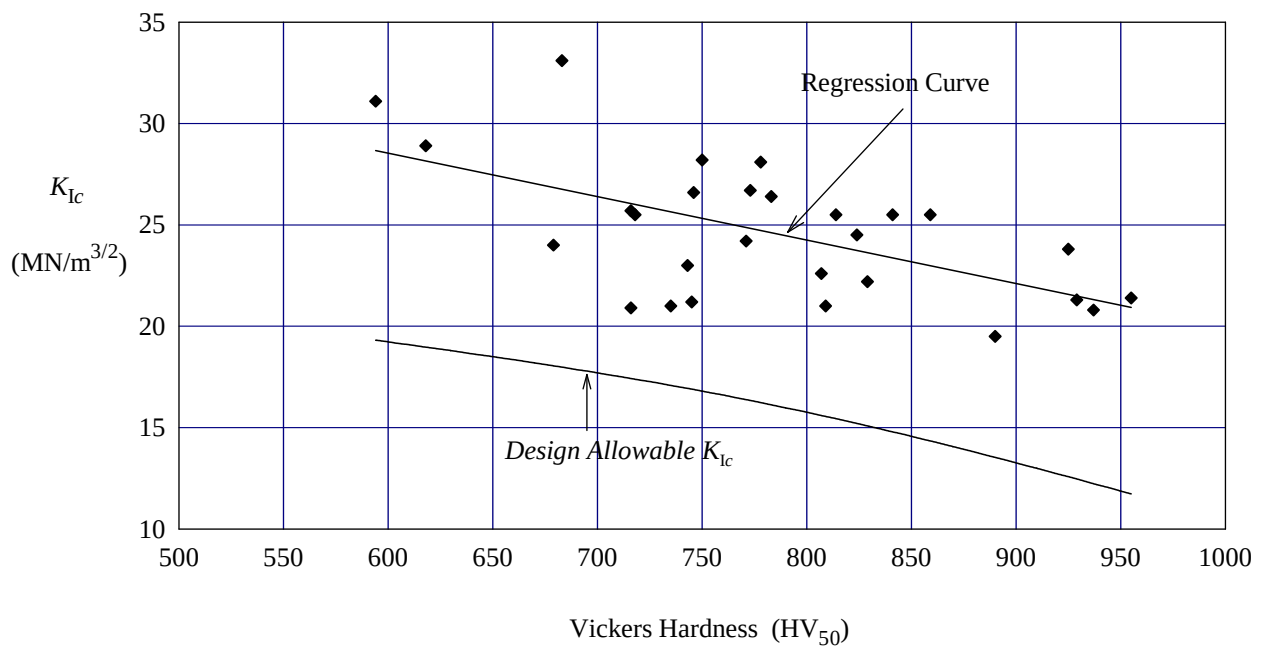


FIGURE 5 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HV₅₀) FOR CLASS IIB MARTENSITIC WHITE CAST IRON (Data used to construct Tables 8.3.19 to 8.3.24*)

* Raw data not available in all instances.

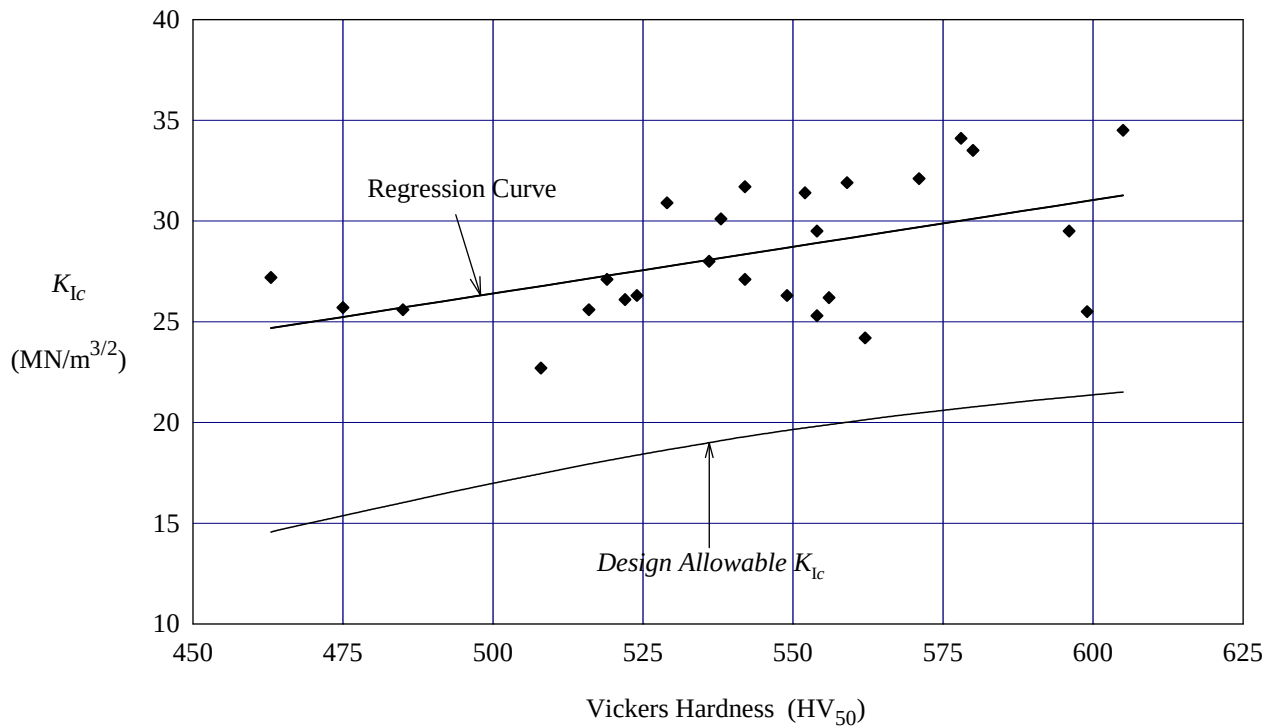


FIGURE 6 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HV₅₀) FOR CLASS IID AUSTENITIC WHITE CAST IRON (Data used to construct Tables 8.3.9 to 8.3.14*)

* Raw data not available in any instance.

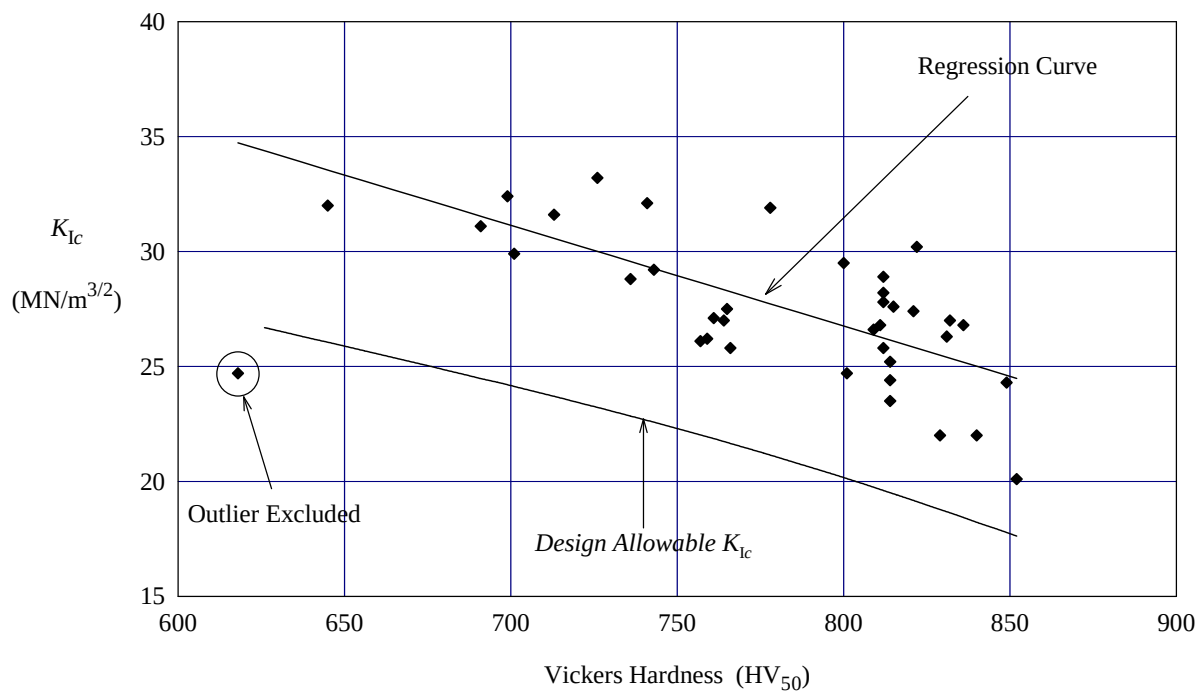


FIGURE 7 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HV₅₀) FOR CLASS IID MARTENSITIC WHITE CAST IRON* (Data used to construct Tables 8.3.25 to 8.3.29[†])

* 'Design Allowable K_{Ic} ' curve not calculated for $618 \leq HV_{50} \leq 626$ (refer to Table E5.5).

[†] Raw data not available in any instances.

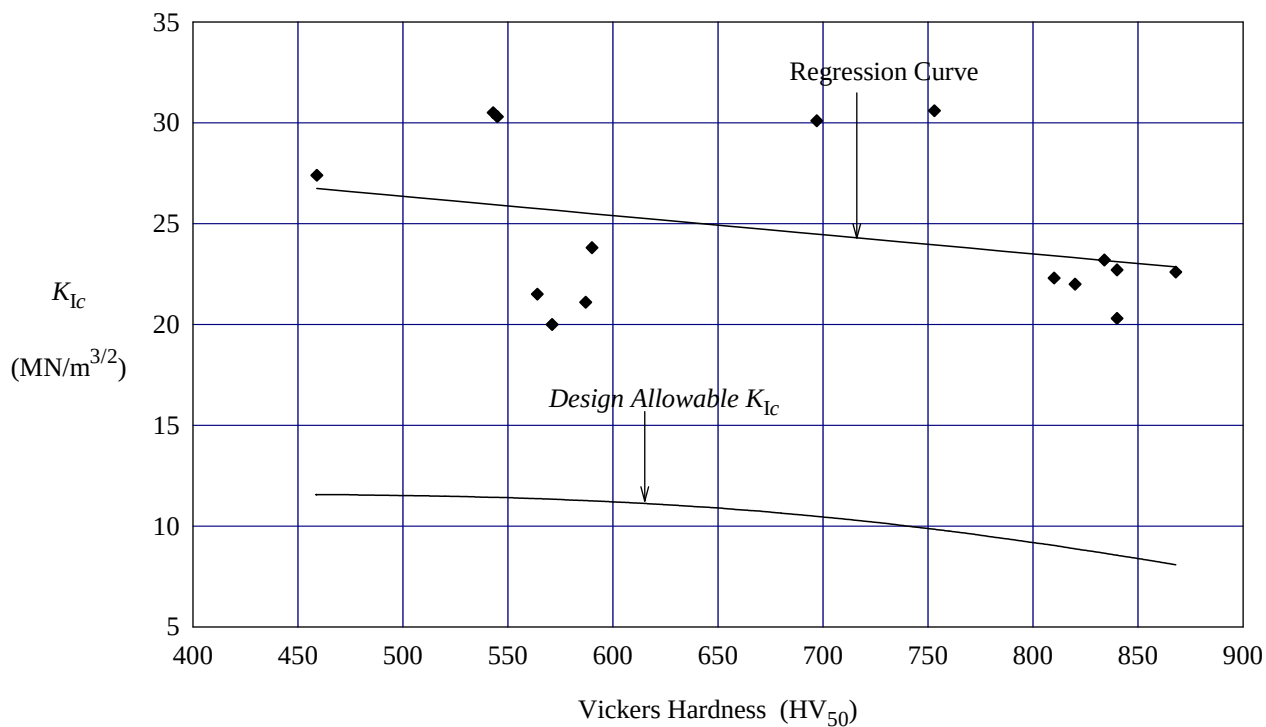


FIGURE 8 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HV₅₀) FOR CLASS IIIA WHITE CAST IRON* (Data used to construct Tables 8.3.15, 8.3.16, 8.3.30 and 8.3.31[†])

* Regression curve not significant at 5 per cent level.

[†] Raw data not available in any instance.

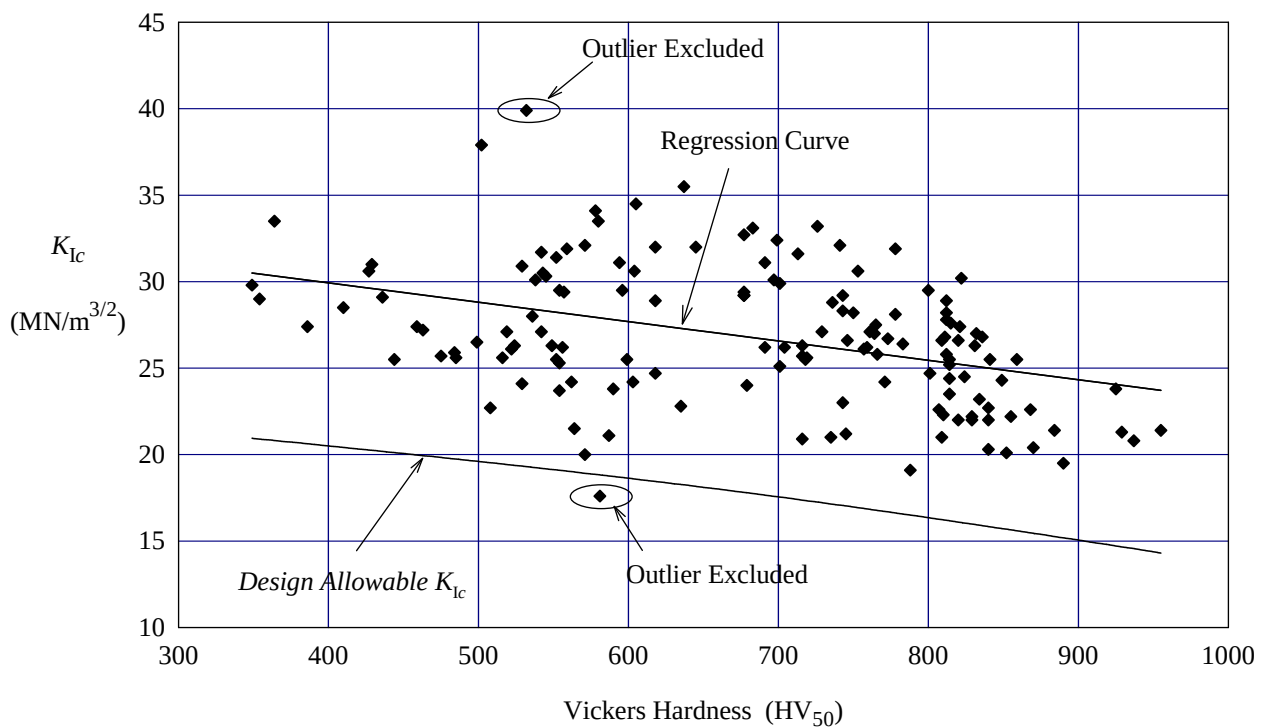


FIGURE 9 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND HARDNESS (HV₅₀) FOR WHITE CAST IRON (Data used to construct Tables 8.3.1 to 8.3.36*)

* Raw data not available in all instances.

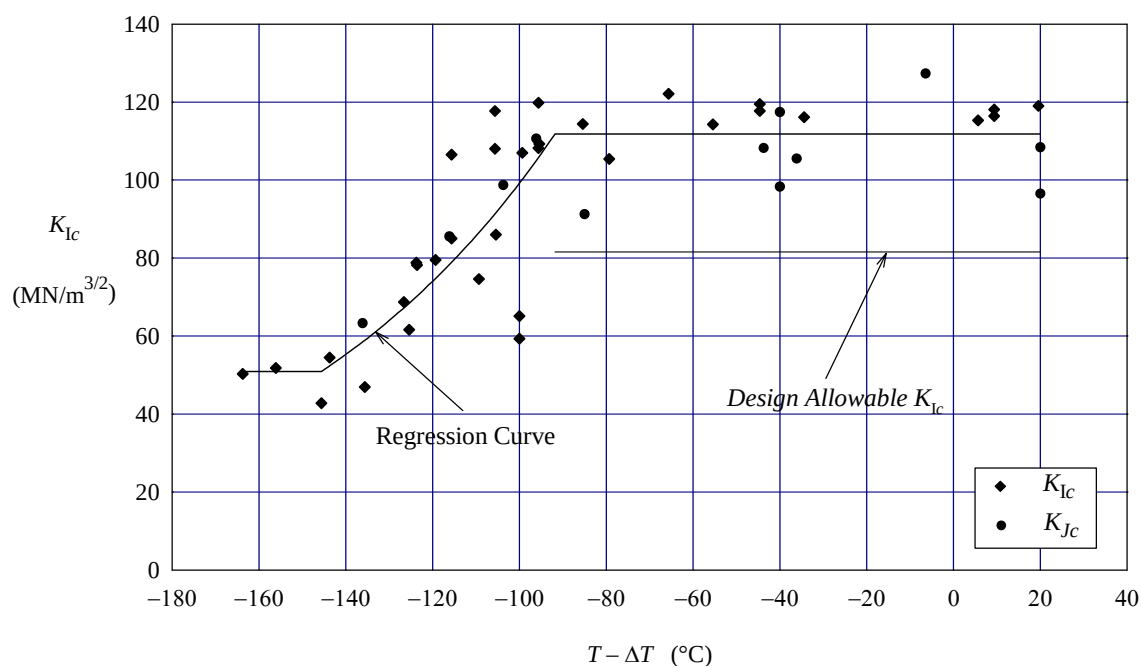


FIGURE 10 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND NORMALISED TEMPERATURE (°C) FOR GGG-35.3 FERRITIC DUCTILE IRON* (Data used to construct Table 8.5.6[†]. See Appendix E, Section E3.3 for details of the normalisation procedure applied)

* The data in this figure have been normalised (see Appendix E, Section E3.3).

† Raw data not available in all instances.

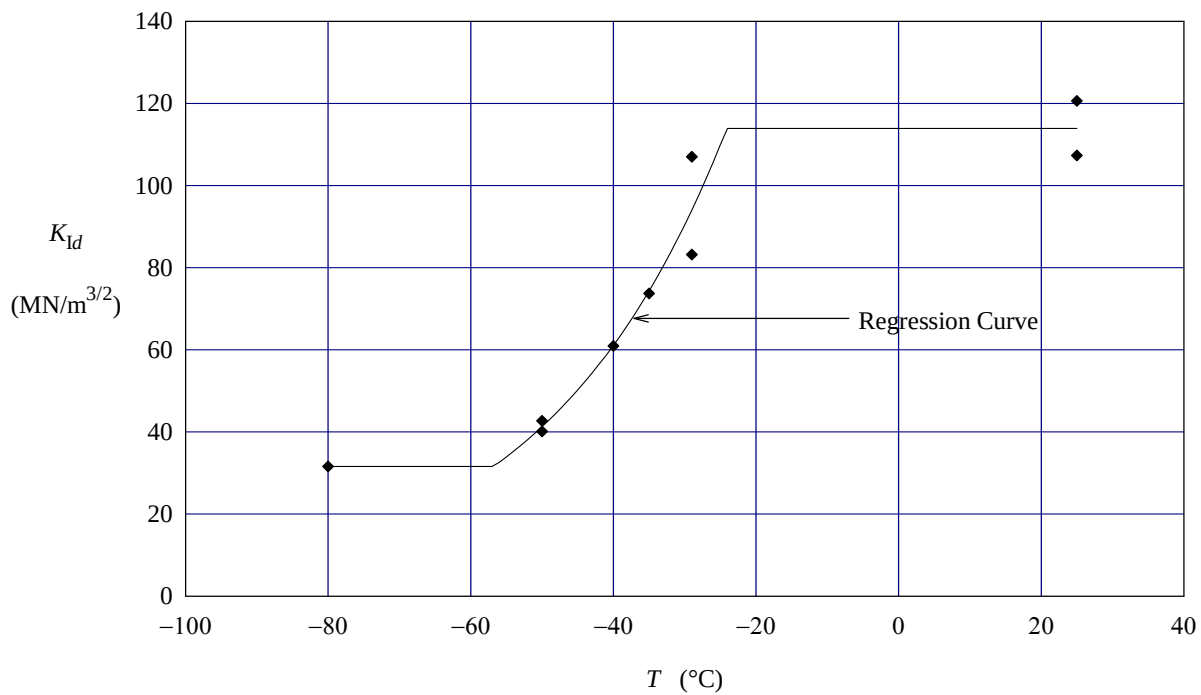


FIGURE 11 RELATIONSHIP BETWEEN DYNAMIC FRACTURE TOUGHNESS AND TEMPERATURE ($^{\circ}\text{C}$) FOR GGG-35.3 FERRITIC DUCTILE IRON (Data used to construct Table 9.1.3)

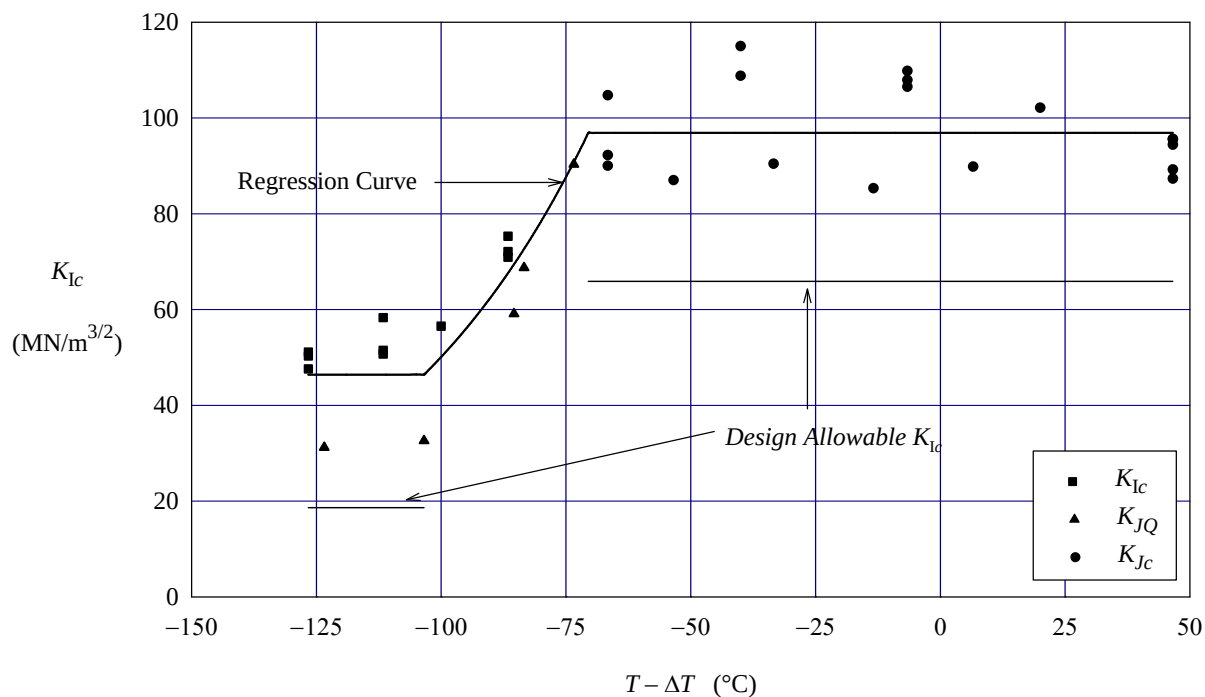


FIGURE 12 RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND NORMALISED TEMPERATURE ($^{\circ}\text{C}$) FOR GGG-40 FERRITIC DUCTILE IRON^{*†} (Data used to construct Table 8.5.7. Refer to Appendix E, Section E3.3 for details of the Normalisation procedure applied)

^{*} The data in this figure have been normalised (see Appendix E, Section E3.3).

[†] Regression curve not significant at 5 per cent level.

5.3 Application of Group Analysis Method

Owing to the cost and complexity of fracture toughness testing, the number of tests performed on a specific material under identical conditions is usually too small to constitute a statistically significant sample. This is because small samples provide uncertain estimates of the variance of the whole population, and consequently any design allowable values predicted cannot be relied upon. A group of 30 or more values is generally required if a meaningful statistical analysis is to be performed.

The sample sizes obtained from the various Derivations were generally less than 30. A reasonable estimate of population variance can be made by grouping samples from non-identical but similar material specifications. Such groups do not, however, constitute a true statistical sample. For this reason the Group Analysis Method was developed.

The data have been grouped under the specific material grade, and the appropriate region on the transition curve for ductile irons, where possible.

The lack of any true samples of 30 or more values meant that a considerable number of generalisations and estimations were necessary in order to make it possible for a statistical analysis using the Group Analysis Method to be performed at all. As a result of this, the analyses represented by Tables 5.2, 5.3a and 5.3b cannot be claimed to be statistically rigorous and any design values obtained through their use should be treated with appropriate caution (see Appendix F for further details).

5.3.1 General notes on Group Analysis Method

(a) Classification

The Group Analysis Method involves categorising data according to particular material characteristics, such as chemical composition and microstructure, and for ductile irons the corresponding region of the brittle-to-ductile transition curve. The mean K_{IC} value for a defined group is then determined, and subsequently the *Design Allowable* K_{IC} .

The *Design Allowable* K_{IC} values calculated using this technique appear in Tables 5.2, 5.3a and 5.3b. These were derived assuming a 99 per cent probability of survival with a 95 per cent level of confidence. For alternative criteria, see Section F2.

The relevant theory and procedures adopted are outlined in Appendix F, and the designer should be familiar with these before utilising any of the parameters deduced from this method.

Table 5.2 presents static fracture toughness data obtained from tests that were generally conducted at room temperature. The materials in this table are only mildly sensitive to temperature, and hence the values quoted may be suitable for use at other temperatures. All material groups passed the Normality test at the 5 per cent level of significance.

The white irons were classified according to their composition, and, where sufficient data were available, microstructure.

Tables 5.3a and 5.3b comprise two types of results:

- (a) Static fracture toughness, and
- (b) Dynamic fracture toughness.

The parameters of Table 5.3a are only likely to be of use in instances where the designer has minimal knowledge of the material specification being used because the table comprises the following two groups.

- (1) Materials that failed the Normality test at a significance level of 5 per cent.
- (2) Material groups that were formed from a wide pool of data (ductile irons).

Most ductile iron groups were formed from a wide range of material specifications, and were classified according to their location on the brittle-to-ductile transition curve. The relevant criteria employed are listed in Appendix F, Section F5.

Additionally, data in the transition region were sub-divided into three distinct zones according to the temperature at which testing was conducted.

Many of the ductile iron groups formed failed the Normality test at the 5 per cent level of significance.

The k_1 factors (which relate the design allowable to the mean fracture toughness) for ductile iron groups are generally low, owing to the high values of standard deviation that result from the wide range of data considered.

When deciding upon the appropriate k_1 factor to use for materials that experience a brittle-to-ductile transition, the designer should take note of all relevant data relating K_{Ic} to temperature for the particular specification in order to judge the region of the curve in which the particular point should be classified.

When forming groups on which to perform statistical analyses, data from certain tables were excluded as their inclusion would have caused an unrealistically high level of scatter.

A group for tests conducted at room temperature was also analysed, as was a similar set of data comprising malleable and ductile iron.

(b) Analysis

The *Design Allowable* K_{Ic} is calculated from the relationship:

$$\text{Design Allowable } K_{Ic} = k_1 \times (K_{Ic})_{mean} \quad (5.1)$$

The factor k_1 relates to a chosen probability of survival, a selected confidence level and the coefficient of variation, cv. The values presented in Tables 5.2, 5.3a and 5.3b assume a 99 per cent probability of survival with a 95 per cent level of confidence.

$(K_{Ic})_{mean}$ refers to the average K_{Ic} value for the particular material group.

5.3.2 Determination of *Design Allowable* K_{Ic} or K_{Id} for a particular material specification sub-group

For instances where users have their own test data, or where they wish to determine the *Design Allowable* K_{Ic} for a particular material specification (or sub-group) that belongs to one of the parent data groups listed in Tables 5.2 or 5.3a and 5.3b, the procedure outlined in this sub-section can be used to obtain a more statistically rigorous value of the *Design Allowable* K_{Ic} .

The procedure involves comparing the difference between the mean and the lower confidence limit for the

particular material specification, or sub-group, (Δ_1) with that for the corresponding parent group (Δ_2).

The parent groups are the material groups in Tables 5.2, 5.3a and 5.3b.

The difference between the mean and its lower confidence limit, Δ , for a one-sided confidence interval is given by:

$$\Delta = \frac{s}{\sqrt{n}} t_{\alpha, v}, \quad (5.2)$$

where s is the standard deviation and

$t_{\alpha, v}$ is the Student's t -distribution factor for a confidence level of α and $v = n - 1$ degrees of freedom.

Δ_1 and Δ_2 are calculated using Equation (5.2).

A Design Allowable K_{Ic} can then be obtained from the relationship:

$$\text{Design Allowable } K_{Ic} = k_1 \times (K_{Ic})_{mean} - (\Delta_1 - \Delta_2). \quad (5.3)$$

Note that k_1 refers to the value for the parent group.

For example, considering Class 30 grey cast iron:

$$(K_{Ic})_{mean} = 21.0 \text{ MN/m}^{3/2}, s = 2.2 \text{ MN/m}^{3/2} \text{ and } n = 5.$$

Hence,

$$\begin{aligned} \Delta_1 &= \frac{2.2}{\sqrt{5}} \times t_{0.95, 5-1} \\ &= 2.1 \text{ MN/m}^{3/2}. \end{aligned}$$

This value appears in Table 5.4.

The material belongs to the Grey Cast Iron group in Table 5.2, for which:

$$s = 2.7 \text{ MN/m}^{3/2}, n = 28 \text{ and } k_1 = 0.54.$$

Hence,

$$\begin{aligned} \Delta_2 &= \frac{2.7}{\sqrt{28}} \times t_{0.95, 28-1} \\ &= 0.9 \text{ MN/m}^{3/2}. \end{aligned}$$

This value appears in Table 5.20.

Consequently, for Class 30 Grey Cast Iron the *Design Allowable* K_{Ic} is given by:

$$\begin{aligned}\text{Design Allowable } K_{Ic} &= (21.0 \times 0.54) - (2.1 - 0.9) \\ &= 10.1 \text{ MN/m}^{3/2}.\end{aligned}$$

From Table 5.2, the *Design Allowable* K_{Ic} for the grey cast iron parent group is $9.7 \text{ MN/m}^{3/2}$.

As the calculated design allowable value for Class 30 Grey Cast Iron is greater than that for the parent group, assuming a *Design Allowable* K_{Ic} of $9.7 \text{ MN/m}^{3/2}$ will provide a more conservative solution for this particular specification.

As a further example, consider 20Cr-Mo Class IID Austenitic White Cast iron (data from Table 8.3.14) for which:

$$(K_{Ic})_{mean} = 28.4 \text{ MN/m}^{3/2}, s = 3.8 \text{ MN/m}^{3/2} \text{ and } n = 6.$$

From which,

$$\Delta_1 = 3.1 \text{ MN/m}^{3/2}.$$

This value appears in Table 5.9.

The material belongs to the Class IID Austenitic White Cast Iron group in Table 5.2, for which:

$$s = 3.3 \text{ MN/m}^{3/2}, n = 43 \text{ and } k_1 = 0.63,$$

from which,

$$\Delta_2 = 0.9 \text{ MN/m}^{3/2}.$$

The value appears in Table 5.20.

Consequently, for 20Cr-Mo Class IID Austenitic White Cast iron, the *Design Allowable* K_{Ic} is given by:

$$\begin{aligned}\text{Design Allowable } K_{Ic} &= (28.4 \times 0.63) - (3.1 - 0.9) \\ &= 15.7 \text{ MN/m}^{3/2}.\end{aligned}$$

The value predicted for this particular specification is more conservative than that calculated for the parent group ($17.7 \text{ MN/m}^{3/2}$, see Table 5.2).

The differences between the means and their corresponding one-sided lower confidence limits (Δ) for the various materials considered, and other relevant information, are listed in Tables 5.4 to 5.19. These values were calculated using the raw and estimated fracture toughness data from the statistical analysis (Tables 5.2, 5.3a and 5.3b), and assume that $\alpha = 0.95$. Instances may arise where the factor provided is not appropriate. Again it should be noted that the analysis is not statistically rigorous, and appropriate caution should be used when applying these factors.

5.3.3 Application of k_1 factor to materials/conditions not considered in the statistical analysis

In instances where a material type/grade listed in this Item has not been included in the statistical analysis, or a fracture toughness value for a material being used in an application does not appear in this Item, the designer may choose to apply the k_1 factor for the particular group to which the material belongs. For example, the k_1 of 0.39 for the Ductile Iron group might be considered to be applicable to DQ&T Tempered Martensitic Ductile Iron at 24°C (75°F) (Table 8.5.17).

The k_1 factor for the Grey Cast Iron group might be applicable for all temperature ranges, as this material experiences no obvious transition. Similarly, the factors provided for the various white cast irons and the Chilled Cast Iron group might be deemed appropriate for any practical application (see the notes on temperature transition for white cast irons in Section 3.2).

Values of k_1 calculated for the ductile iron groups on the upper and lower shelves, and various sections of the transition region, might provide suitable approximations for forms of ductile iron not considered in the analysis, and compacted graphite and malleable cast irons. The k_1 factor calculated for the “Ductile Iron, Upper Shelf” group might also be considered applicable to the “Lower Shelf” group, as the degree of variation in both regions is likely to be similar.