

FRACTURE TOUGHNESS (K_{Ic}) VALUES OF SOME STEELS

1. NOTATION

C_{PSB}	pre-cracked Charpy V-notch slow bend energy	J	ft lbf
C_{SB}	Charpy V-notch slow bend energy	J	ft lbf
C_{VN}	Charpy V-notch energy	J	ft lbf
E	modulus of elasticity	N/m ²	lbf/in ²
G_{Ic}	plain strain Mode I toughness	N/m	lbf/in
J_{Ic}	critical Mode I value of J -integral in plane strain	N/m	lbf/in
k_1, k_2	statistical factors incorporating coefficients of variation of samples, see Section 4, Equations (4.1) and (4.2)		
K	crack-tip stress-field-intensity factor	N/m ^{3/2}	lbf/in ^{3/2}
K_c	plane stress fracture toughness (critical value of stress in intensity plane stress)	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_{Id}	dynamic plane strain fracture toughness in Mode I	N/m ^{3/2}	lbf/in ^{3/2}
T	temperature	°C	°F
ΔT	temperature difference	°C	°F
α	dimensional constant, see Appendix B	10 ³ m ⁻²	in ⁻¹ ft ⁻¹
β	dimensional constant, see Appendix B	°C	°F
γ	dimensional constant, see Appendix B	°C m ² /N	°F in ² /lbf
λ	dimensional constant, see Appendix B	10 ⁶ m ⁻²	10 ³ ft ⁻¹ in ⁻¹
μ	dimensional constant, see Appendix B	10 ⁶ m ⁻³	10 ³ ft ⁻¹ in ⁻²
ν	Poisson's ratio		
σ_p	0.2 per cent proof stress	N/m ²	lbf/in ²

See Appendix A for definition of crack orientation with respect to grain flow.

Both SI and British units are quoted.

* See Data Item No. 80036, "Introduction to the use of linear elastic fracture mechanics in estimating fatigue crack growth rates and residual strength of components".

Suffixes

mean The suffix *mean*, applied to K_{Ic} , refers to the mean fracture toughness values in the tables of Section 8.

1.1 K_{Ic} Conversion Factors

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

Note also that,

$$1 \text{ MN/m}^{3/2} = 31.623 \text{ N/mm}^{3/2} = 1 \text{ MPa } \sqrt{\text{m}} .$$

2. NOTES

2.1 General Notes

This Item presents plane strain fracture toughness (K_{Ic}) values for a variety of steels 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 Data Item No. 80036.

Fracture toughness values are used to determine within LEFM 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.

In thin sections or the more ductile materials, the point of instability is less well-defined and depends on crack tip plasticity, thickness and other geometrical aspects (see also Section 5.1 of Data Item No. 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 . 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. A worked example illustrating a use of fracture toughness data is given in Section 6.

Some of the plane strain K_{Ic} values that are in this Item have been calculated from J_{Ic} values. The path independent J -integral, or energy line integral, is applicable to both elastic and plastic behaviour and its value depends upon the near crack tip stress-strain field.

The relationship between J_{Ic} and K_{Ic} is given by Equation (2.1) which is valid under linear-elastic plain strain conditions.

$$J_{Ic} = G_{Ic} = \frac{1 - \nu^2}{E} K_{Ic}^2 . \quad (2.1)$$

Throughout this Item a modulus of elasticity, E , equal to 200 GN/m^2 ($29 \times 10^6 \text{ lbf/in}^2$) and a Poisson's ratio, ν , equal to 0.3 have been used in deriving K_{Ic} from J_{Ic} values.

2.2 Test Conditions

The data have been taken from tests performed in non-corrosive environments at temperatures between -200°C and 150°C (-330°F and 300°F) on specimens cut from plate, bar, forgings, castings, *et cetera*, manufactured from British and U.S. standard specification materials. The tests have been carried out in accordance with the British Standards Institution's or American Society for Testing and Materials' standards (see References 38, 41 and 42). Briefly, these tests involve applying a steadily increasing load to fracture a specimen containing a machined notch which has been lengthened and sharpened by fatigue cracking. Further information on testing is given in Data Item No. 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. To achieve this requirement for low strength, high toughness materials may involve using very thick specimens, often thicker than 300 mm (12 in). For such materials, this stipulation is not always met and the results are invalid according to the standards. However, if the load/extension record shows a "pop-in", that is, a sudden extension of the crack occurring with no increase in load, then it is usually considered that plane strain conditions have been achieved and a valid K_{Ic} result obtained. Such data are marked with an asterisk in the tables of Section 8.

2.3 Presentation of Data

The results of the fracture toughness tests evaluated are tabulated in Section 8. Details quoted include test temperature, crack orientation relative to grain flow, chemical analysis, heat treatment and proof stress. Where two values of thickness appear in the column headed "Form and thickness" the first value refers to the thickness of the test specimen while the second value refers to the thickness of the product, plate, forging, *et cetera*, 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.

In order to assist in the interpolation of K_{Ic} and σ_p values in the tables, selected data are represented graphically in Section 7 where the typical dependence of K_{Ic} and σ_p on temperature is illustrated. The graphs have been drawn by eye through plots of mean K_{Ic} and σ_p values, using, in some cases, relatively few points. Typical values have been chosen to construct the graphs because the wide variety of heat treatments, chemical analyses, *et cetera*, of the materials leads to a fairly wide scatter.

As mentioned in Section 2.1, some of the K_{Ic} values that are in this Item have been derived from J_{Ic} values. Such values are presented in italics in the tables. All the values presented in the tables, with the exception of those already mentioned in Section 2.2, were found to meet the ASTM/BSI K_{Ic} thickness stipulation.

For some of the materials in this Item only room temperature values of proof stress were available and it was these values that were used to ascertain whether or not the ASTM/BSI thickness stipulation had been met. Where this is the case two numbers appear in the column headed "No. of tests", the first of which gives the number of test specimens that met the ASTM/BSI thickness requirement. The second number gives the number specimens that narrowly missed the thickness requirement. In the latter cases the test results could well have been shown to satisfy the requirement had more accurate values of proof stress and, in the cases of data derived from J_{Ic} , modulus, been available. The reason for this contention is that the room temperature values of proof stress used were probably lower than the true values at the lower temperatures at which the tests were conducted, and for which σ_p data were lacking, thus making the requirement more stringent.

For the statistical confidence with which the K_{Ic} data may be applied, see Section 4.

3. FACTORS AFFECTING FRACTURE TOUGHNESS

The following sections explain the effect on 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 toughness.

3.1 Heat Treatment

Although a proof or yield stress is a material property, the heat treatment used to achieve a value of proof stress will also influence the toughness. **It is important to realise that a heat treatment giving a higher proof stress will, in general, lead to lower toughness.** This is clearly illustrated in Sketches 7.4, where an 18Ni maraging steel with different heat treatments exhibits reduced toughness for increasing strength levels: σ_p equal to 1380, 1720 and 2070 MN/m² (200 000, 250 000 and 300 000 lbf/in²).

Markedly reduced toughness may be caused by a high temperature heat treatment followed by quenching leading to martensitic embrittlement or low temperature tempering which may promote either tempering embrittlement or strain ageing. These effects may arise unintentionally as a result of production processes, for example, welding.

3.2 Crack Orientation

The notation for crack orientation relative to material grain flow is defined in Appendix A. Fracture toughness is reduced by the presence of inclusions. These inclusions are the main cause of the disparity in fracture toughness values for different crack orientations, since after heavy mechanical working, the shape of the inclusions is changed. The test specimen orientation, if known, is quoted in the tables of Section 8.

3.3 Temperature

Over the range considered in this Item, fracture toughness decreases with decreasing temperature. Some materials, notably ferritic steels, are, however, more sensitive to temperature changes than others. For example, 18Ni maraging steels exhibit a fairly linear reduction in toughness with decreasing temperature, but low alloy, low strength steels such as ASTM A533B show a sharp drop in toughness over a 50°C (90°F) range at about room temperature. The relationship between K_{Ic} and temperature is shown in Sketches 7 for different materials. Also shown is the relationship between σ_p and temperature.

3.4 Environment

The data in this Item refer to tests carried out in normal atmospheric conditions. In service, materials exposed to hydrogen, corrosive agents or nuclear irradiation will have reduced fracture toughness. 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.

3.5 Rate of Loading

The data 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 0.47 – 2.5 MN/(m^{3/2}s)(430 – 2300 lbf/(in^{3/2} s)). This precludes, for example, impact loading.

4. STATISTICAL ANALYSIS OF DATA

4.1 Introduction

Before the K_{Ic} values can be applied with any confidence, an allowable value for the design in hand should be determined. Owing to the cost and complexity of fracture toughness testing, the number of tests performed on a specific material at a given temperature, orientation, *et cetera*, is more often than not too small to constitute a statistically significant sample. This section explains two basic procedures for obtaining a K_{Ic} value for use in design. The procedure selected depends upon the number of K_{Ic} values available for a particular material under specific test conditions. With 30 or more values a statistical analysis can be conducted, the results of which would enable a suitable design value to be obtained. For these cases, various rigorous statistical analyses and methods, such as those used in Section 4.2, may be found in Data Item No. 91041^{*}; they rely solely upon the data from the sample and assume only a Normal distribution for the population. If it is assumed that the sample is of Normal distribution and has a coefficient of variation close to the typical value of 0.18, Figure 4.1 may be used directly to find the allowable K_{Ic} . With a sample size less than 30, a rigorous value for allowable K_{Ic} is unobtainable; but an approximate value can be found from Figure 4.2, which was derived from the typical scatter of K_{Ic} in the population.

4.2 Large Samples

The results of an analysis of a sample of 30 or more values are generally considered to be statistically significant in that they enable the fit of the sample to a Normal distribution to be assessed. In this Item there are four samples of 35 or more values obtained from tests for which the conditions were identical, and one sample of 34 values for A533B steel for which the specimens were identical except for variations in their thicknesses.

These samples were tested for normality using ESDUpac A9141[†] which also gives the mean, the standard deviation and the coefficient of variation of the sample being tested. (The coefficient of variation of a sample is the standard deviation of the sample divided by the sample mean.) The significance level of the test for normality is the percentage of samples from Normal populations that will be rejected by the test as non-normal. The results of the analyses of the samples are presented in Table 4.1. It can be seen that the coefficients of variation of the samples are similar, as are the sample sizes.

TABLE 4.1

Material	Table	Sample mean (K_{Ic}) _{mean} MN/m ^{3/2} (10 ³ lbf/in ^{3/2})	Sample standard deviation MN/m ^{3/2} (10 ³ lbf/in ^{3/2})	Sample coefficient of variation	Number of values	Hypothesis of normality accepted at significant level of	
						0.2 %	2.5%
A533B	8.1(v)	40 (36)	6.8 (6.2)	0.17	34	Yes	Yes
D6AC	8.14	74 (67)	12.3 (11.2)	0.17	35	Yes	Yes
D6AC	8.14	75 (68)	13.3 (12.1)	0.18	47	Yes	No
D6AC	8.14	92 (84)	16.3 (14.8)	0.18	52	Yes	Yes
D6AC	8.14	67 (61)	12.5 (11.4)	0.19	56	No	No

* Data Item No. 91041, "The statistical analysis of data from Normal distributions, with particular reference to small samples".

† ESDUpac No. A9141, "The statistical analysis of data from Normal distributions, with particular reference to small samples".

An allowable value of K_{Ic} may be obtained from Equation (4.1), in which k_1 relates to a chosen probability of survival and a chosen confidence level and $(K_{Ic})_{mean}$ is the sample mean. For an explanation of the term confidence level, see Data Item No. 91041, Section 6.

$$K_{Ic} = k_1 \times (K_{Ic})_{mean} \quad (4.1)$$

For the materials of Table 4.1 it was established that k_1 varied only slightly for the range of coefficient of variation and sample size seen in Table 4.1 (those are, 0.17 – 0.19 and 34 – 56 respectively). Figure 4.1 was constructed to give values of k_1 and therefore used a coefficient of variation of 0.18 and a sample size of 45, these being the respective mean values for the five samples in Table 4.1.

Note that using combinations of low percentage probabilities of exceeding the allowable value and low percentage confidence levels may lead to cases where the value of k_1 obtained is greater than the minimum value of the sample given in the tables. In such cases it is suggested that further consideration is given to selecting a value to be used for the design in hand.

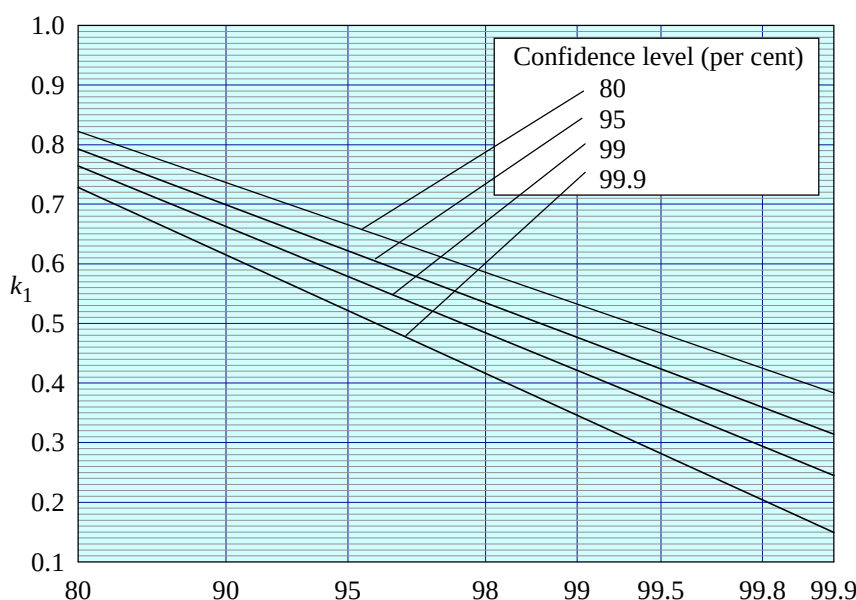


FIGURE 4.1 STATISTICAL FACTOR k_1 USED TO ESTIMATE ALLOWABLE VALUE OF K_{Ic} FOR THE MATERIALS OF TABLE 4.1

4.3 Small Samples

Samples of less than 30 values are not considered statistically significant in themselves and so the following method was adopted to analyse the data.

- (i) The arithmetic mean, $(K_{Ic})_{mean}$, was determined for a group of 8 or more results for which the chemical analysis, heat treatment, test temperature, *et cetera* were identical. The only factor that did vary within some of the sets was the thickness of the test specimen.
- (ii) Each individual value was divided by the mean of the group to obtain a set of $K_{Ic} / (K_{Ic})_{mean}$ values which were then treated as the normalised sample values.

- (iii) Procedures (i) and (ii) were repeated for all other such sets.
- (iv) The sets were tested for normality using ESDUpac A9141.
- (v) The sets for which the hypotheses of normality were accepted, 16 in all, were compared to determine whether or not they could have originated from the same Normal population*. The hypothesis of a shared parent population was accepted for 13 of the sets. These 13 sets are marked with crosses in the columns headed "No. of tests" in the tables of Section 8.
- (vi) The 13 sets were combined and analysed as one sample of 281 values.

The analysis of this sample gave 0.16 as a point estimate of the population coefficient of variation.

An allowable value of K_{Ic} may be obtained from Equation (4.2), in which k_2 relates to a chosen probability of survival and a chosen confidence level.

$$K_{Ic} = k_2 \times (K_{Ic})_{mean} . \quad (4.2)$$

Figure 4.2 gives the value of k_2 calculated from the combined sample of 281 values.

For example, to ensure that K_{Ic} will not be less than the design value 99 times out of a hundred with 95 per cent confidence, a value of k_2 equal to 0.6 is read from Figure 4.2. Equation (4.2) then gives the design value as

$$K_{Ic} = 0.6(K_{Ic})_{mean} ,$$

where $(K_{Ic})_{mean}$ is obtained from the tables of Section 8.

The worked example illustrates the use of this section.

It is important to note that in the smaller samples there is more uncertainty as to where the mean of the population lies in relation to the mean of the sample, and that this uncertainty will be carried through to the allowable value that is obtained. Note also that using combinations of low percentage probabilities of exceeding the allowable value and low percentage confidence levels may lead to cases where the allowable value of K_{Ic} obtained is greater than the minimum value in the tables. In such cases it is suggested that consideration is given to selecting a value to be used for the design in hand.

* For details of the method used, see "Metallic Materials Data Handbook", Volume 1, Section 1, Appendix 5.

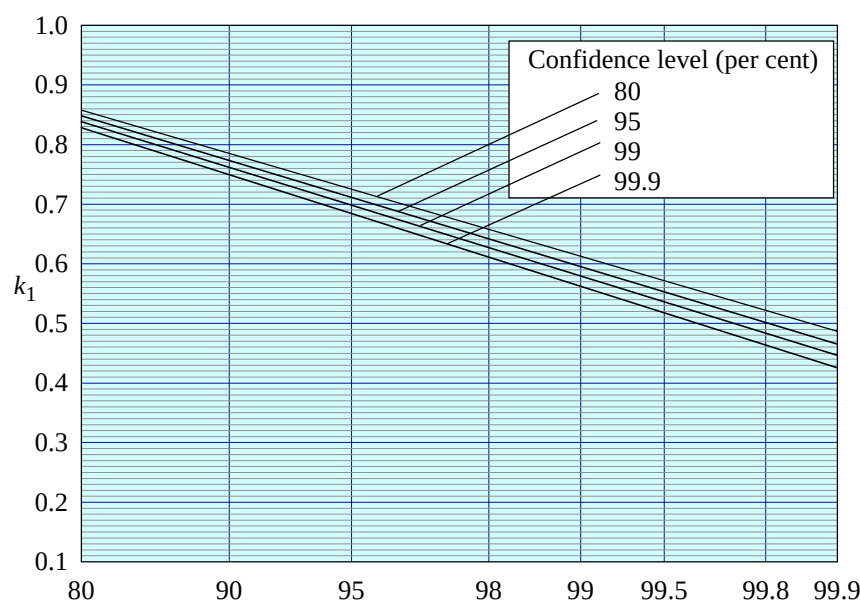


FIGURE 4.2 STATISTICAL FACTOR k_2 USED TO ESTIMATE ALLOWABLE VALUE OF K_{Ic} FOR SMALL SAMPLES

5. DERIVATION AND REFERENCES

5.1 Derivation

This section lists selected sources that have assisted in the preparation of this Item.

1. MOWBRAY, D.F.
BROTHERS, A.J.
YUKAWA, S. Fracture toughness determinations of A302-B and Ni-Mo-V steels with various size specimens. *Transactions American Society of Mechanical Engineers, Journal of Basic Engineering*, Vol. 88, pp. 783-791, December 1966.
2. LANDERMAN, E.
YANICHKO, S.E. Determination of fracture toughness of heavy section pressure vessel steels using a fracture mechanics approach. Welding Research Council, UK, Bulletin No. 120, February 1967.
3. WESSEL, E.T. State of the art of the WOL specimen for K_{Ic} fracture toughness testing. *Engineering Fracture Mechanics*, Vol. 1, No. 1, pp. 77-103, 1968.
4. KULA, E.B.
ANCTIL, A.A. Tempered martensitic embrittlement and fracture toughness in SAE 4340 steels. *American Society for Testing and Materials, Journal of Materials*, Vol. 4, No. 4, pp. 817-841, December 1969.
5. GENTILICORE, V.J.
PENSE, A.W.
STOUT, R.D. Fracture toughness of pressure vessel steel weldments. *Welding Journal*, Vol. 49, pp. 341s-353s, August 1970.
6. ROLFE, S.T.
NOVAK, S.R. Review of developments in plane strain fracture toughness testing, *American Society for Testing and Materials, Special Technical Publication 463*, pp. 124-159, 1970.

7. SHOEMAKER, A.K.
ROLFE, S.T. The static and dynamic low temperature crack toughness performance of 7 structural steels, *Engineering Fracture Mechanics*, Vol. 2, No. 4, pp. 319-339, June 1971.
8. KÁLNA, K.
ŠTĚPÁNEK, S. An approach to fracture-safe design, manufacture and operation of pressure vessels. In: *Practical application of fracture mechanics to pressure vessel technology*, Institution of Mechanical Engineers, London, UK, pp. 251-256, 1971.
9. FEDDERSON, C.E.
MOON, D.P.
HYLER, W.S. Crack behaviour in D6AC steels. Metals and Ceramics Information Center, Battelle Laboratories, Columbus, Ohio, USA, MCIC-72-04 (AD 737779), January 1972.
10. ROBINSON, J.N.
TUCK, C.W. The relationship between microstructure and fracture toughness for a low-alloy steel. *Engineering Fracture Mechanics*, Vol. 4, No. 2, pp. 377-392, June 1972.
11. FISHER, D.M.
REPKO, A.J. Plane strain fracture toughness tests on 2.4 and 3.9 inch thick maraging steel specimens at various yield strength levels. *Journal of Materials*, Vol. 7, No. 2, pp. 167-174, June 1972.
12. McCABE, D.E. Evaluation of the compact tension specimen for determining plane strain fracture toughness of high strength materials. *Journal of Materials*, Vol. 7, No. 4, pp. 449-454, December 1972.
13. SAILORS, R.H.
CORTEN, H.T. Relationship between material fracture toughness using fracture mechanics and transition temperature tests. *Fracture Toughness, Proceedings of the 1971 National Symposium on Fracture Mechanics, Part II, American Society for Testing and Materials, Special Technical Publication 514*, pp. 164-191, 1972.
14. BARSOM, J.M.
PELLEGRINO, J.V. Relationship between K_{IC} and plane strain tensile ductility and microscopic mode of fracture. *Engineering Fracture Mechanics*, Vol. 5, No. 2, pp. 209-221, June 1973.
15. MATHEWS, W.T. Plain strain fracture toughness K_{IC} data handbook. Army Materials and Mechanics Research Center, Watertown, Mass, USA, AMMRC-MS-73-6 (AD773673), December 1973.
16. LOGSDON, W.A. An evaluation of the crack growth and fracture properties of AISI 403 modified 12 Cr stainless steel. *Engineering Fracture Mechanics*, Vol. 7, No. 1, pp. 23-40, March 1975.
17. WOOD, W.E. Effect of heat treatment on the fracture toughness of low alloy steels. *Engineering Fracture Mechanics*, Vol. 7, No. 2, pp. 219-234, June 1975.
18. PARKER, E.R.
ZACKEY, V.F. Microstructural features affecting fracture toughness of high strength steels. *Engineering Fracture Mechanics*, Vol. 7, No. 3, pp. 371-375, September 1975.
19. BARNBY, J.T.
AL-DAIMALANI, I.S. Assessment of the fracture toughness of cast steels, Part 1: low alloy steels. *Journal of Materials Science*, Vol. 11, No. 11, pp. 1979-1988, November 1976.

20. LOGSDON, W.A. Elastic-plastic (J_{Ic}) fracture toughness values, their experimental determination and comparison with conventional linear elastic (K_{Ic}) fracture toughness values for five materials. *American Society for Testing and Materials, Special Technical Publication 590, Mechanics of Crack Growth*, pp. 43-60, 1976.
21. FLOREEN, S. The fracture toughness of cast high-strength steels. *Transactions American Society of Mechanical Engineers, Journal Engineering Materials Technology*, pp. 70-75, January 1977.
22. PRIDDLE, E.K. Fatigue crack growth in a high strength steel. In: *Advances in research on the strength and fracture of materials*, 4th International Conference on Fracture, Waterloo, Canada, Vol. 2B – Fatigue, pp. 1249-1257, June 1977.
23. HEBSUR, M.G.
ABRAHAM, K.P.
PRASAD, Y.V.R.K. Effect of electroslag refining on the fracture toughness and fatigue crack propagation rates in heat treated AISI 4340 Steel. *Engineering Fracture Mechanics*, Vol. 13, No. 4, pp. 851-864, 1980.
24. ROBERTS, R.
NEWTON, C. Interpretive report on small-scale test correlations with K_{Ic} data. Welding Research Council, Bulletin 265, ISSN 0043-2326, February 1981.
25. COBANOGLU, M.M
KARDOS, G. Comparison of methods for fracture toughness determination in steels. *American Society for Testing and Materials, Journal of Testing and Evaluation*, Vol. 9, No. 2, pp. 104-110, March 1981.
26. PISARSKI, H.G. Influence of thickness on critical crack opening displacement (COD) and J values. *International Journal of Fracture*, Vol. 17, No. 4, pp. 427-440, 1981.
27. GALLAGHER, J. *Damage tolerant design handbook*. Metals and Ceramics Information Center, Battelle Laboratories, Columbus, Ohio, USA, MCIC-HB-O1R, December 1983.
28. MERKLE, J.G. Examination of the size effects and data scatter observed in small-specimen cleavage fracture toughness testing. Oak Ridge National Laboratory Topical Report, April 1984.
29. STRNADEL, B.
MAZANCOVA, E.
HAVEL, S.
MAZANEC, K. Prediction of fracture toughness for a pressure vessel steel with mixed bainite-ferritic microstructure. *International Journal of Pressure Vessels and Piping*, Vol. 23, pp. 47-60, 1986.
30. McCABE, D.E. Comparison of Weibull and β_{Ic} analysis of transition range fracture toughness data. Oak Ridge National Laboratory Technical Report, January 1992.
31. LANDES, J.D. The effect of size, thickness and geometry on fracture toughness in the transition region. GKSS-Forschungszentrum Geesthacht GMBH, 1992.
32. BROZOVA, A.
RUSCAK, M. The statistical treatment of small specimen fracture toughness data in the transition region. In: *Fatigue and Fracture of Engineering Materials and Structures*. Vol. 16, No. 11, pp. 1203-1212, November 1993.

33. ALEXANDER, D.J.
CHEVERTON, R.D. Fracture properties of specially heat-treated ASTM A508 class 2 pressure vessel steel. *American Society for Testing and Materials, Special Technical Publication. Proceedings of the 23rd National Symposium on Fracture Mechanics*, pp. 365-380, 1993.

5.2 References

The references given are recommended sources of information supplementary to this Item.

34. TADA, H.
PARIS, P.
IRWIN, G. *The stress analysis of cracks handbook*. Del Research Corp., Hellertown, Pennsylvania, USA, 1973.
35. SIH, G.C. *Handbook of stress intensity factors for researchers and engineers*. Institute of Fracture and Solid Mechanics, Lehigh University, Bethlehem, Pennsylvania, USA, 1973.
36. ROOKE, D.P.
CARTWRIGHT, D.J. *Compendium of stress intensity factors*, HMSO, London, UK, 1976.
37. BARSOM, J.M.
ROLFE, S.T. *Fracture and fatigue control in structures*. Prentice Hall, New York, USA, 1977.
38. BSI Methods of test for plane strain fracture toughness (K_{Ic}) of metallic materials. British Standards Institution, London, UK, BS 5447: 1977.
39. HUDSON, C.M.
SEWARD, M.K. A compendium of sources of fracture toughness and fatigue crack growth data for metallic alloys. *International Journal of Fracture*, Vol. 14, No. 4, pp. R151-R184, 1978.
40. MURAKAMI, Y.
AOKI, S. *Stress intensity factors handbook*. Pergamon Press, Oxford, UK, 1988
41. ASTM Standard test method for plane-strain fracture toughness of metallic materials. American Society for Testing and Materials, Philadelphia, USA, ASTM E399-90, ASTM Standards Handbook, 1990.
42. BSI Fracture mechanics toughness tests. Part 1. Method for determination of K_{Ic} , critical $CTOD$ and critical J values for metallic materials. British Standards Institution, London, UK, BS 7448: 1991.
43. ASTM/SAE Metals and alloys in the unified numbering system. 6th Edition. American Society for Testing and Materials and the Society of Automotive Engineers. Joint publication ASTM DS-56E/SAE HS-1086 Feb. 93. ISBN 1-56091-314-2. 1993.
44. ASTM Standard methods for notched bar impact testing of metallic materials. American Society for Testing and Materials, Philadelphia, USA, ASTM E23-94b, 1994.

6. EXAMPLE

6.1 Notation

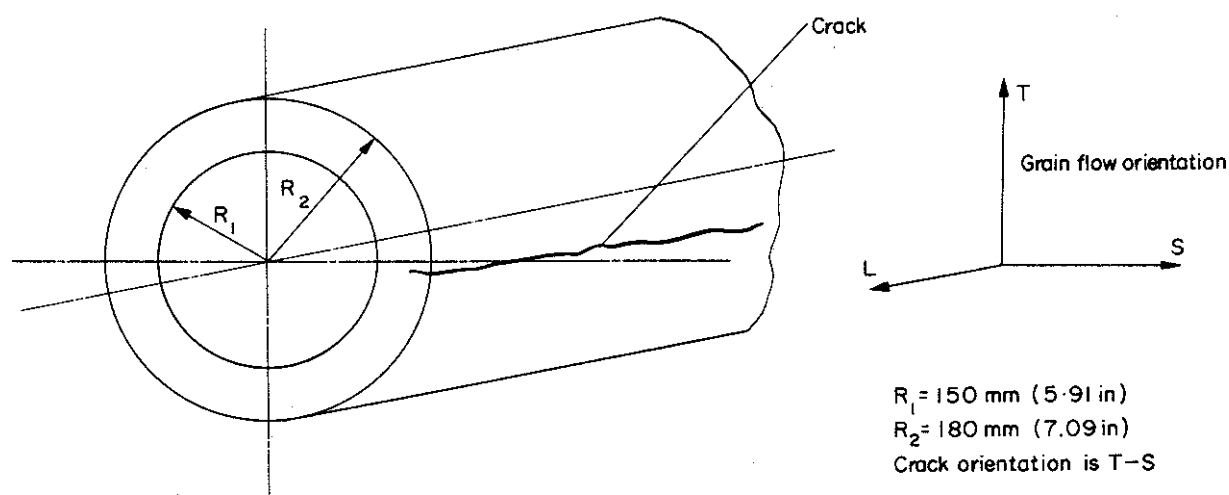
This notation is supplementary to that of Section 1.

K_I	nominal stress intensity factor at crack tip	$\text{N/m}^{3/2}$	$\text{lbf/in}^{3/2}$
P	internal pressure in pipe	N/m^2	lbf/in^2
R_1, R_2	inner and outer radii of pipe respectively	m	in

6.2 Example

A proposed design for part of a chemical plant consists of a long pipe with a 300 mm (11.8 in) bore and an outside diameter of 360 mm (14.2 in) leading from a pressure vessel to a valve. The vessel and the pipe will contain a non-corrosive, liquified gas under a pressure of 33 MN/m² (4790 lbf/in²). When the valve is opened, the temperature near the valve will drop to about -130°C (-200°F). It is required to investigate the fracture toughness of ASTM A302B low alloy, low strength steel to determine whether or not it would be a suitable material for the pipe.

Linear elastic fracture mechanics will be used to determine the likelihood of the pipe failing due to brittle fracture caused by the presence of a crack. In reality, many different crack positions and configurations would be examined, but for the purposes of this example a longitudinal crack on the outside of the pipe will be investigated. The following analysis will determine the maximum size the crack can attain before the pipe will fail due to brittle fracture. That is, when the value of K_I^* calculated reaches the appropriate value of K_{Ic} . The pipe is shown in Sketch 6.1.



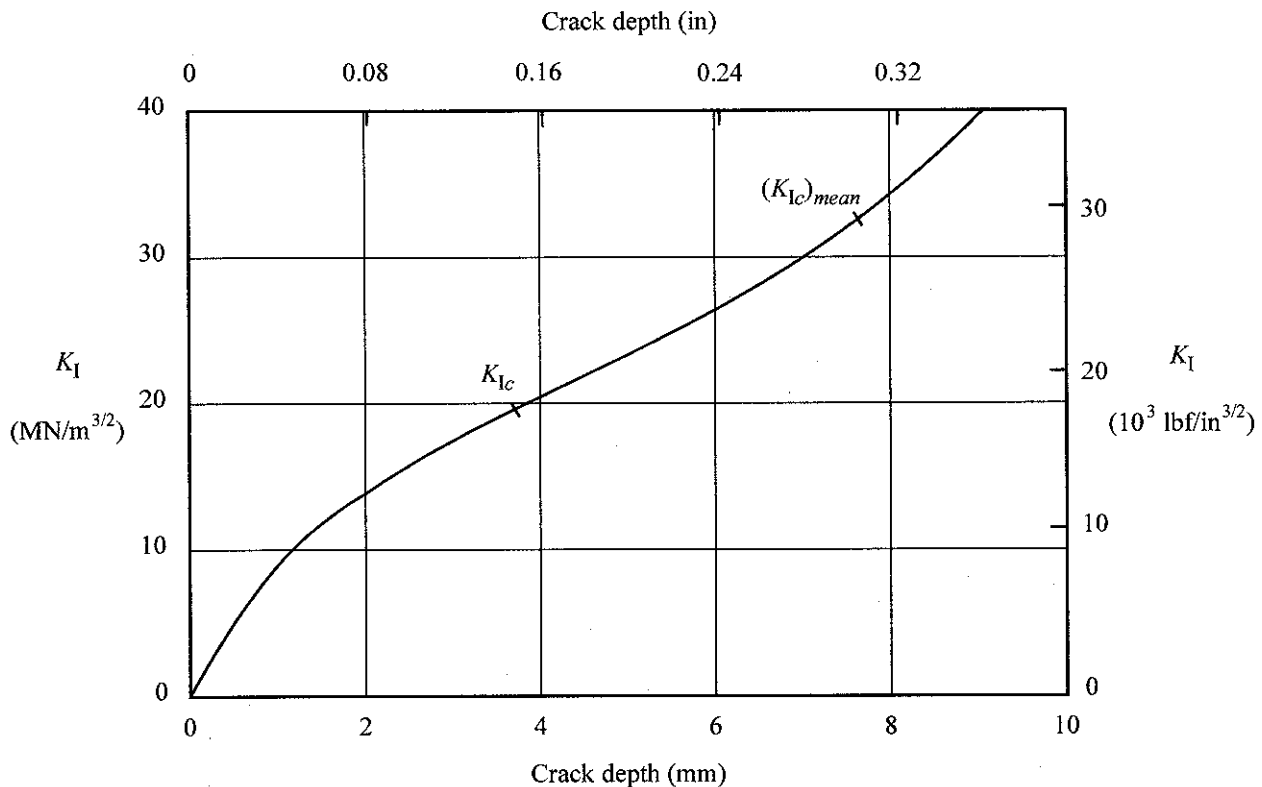
Sketch 6.1 View of pipe and crack

* K_I is used to denote the stress intensity factor in Mode I, appropriate for this situation, where the hoop stress is pulling the crack open in tension.

An analysis of this crack configuration is given in Reference 36, from which the critical crack dimension has been found to be the depth. The stress intensity at the crack tip is dependent on the hoop stress in the pipe in the absence of the crack. Using thick cylinder theory, the hoop stress is given by

$$\frac{2P}{(R_2/R_1)^2 - 1} = \frac{2 \times 33}{(0.18/0.15)^2 - 1} = 150 \text{ MN/m}^2 \text{ (or 21 760 lbf/in}^2\text{)}. \quad (6.1)$$

Using the graphs of Reference 36, Sketch 6.2 may now be constructed showing the variation of K_I with crack depth.



Sketch 6.2 Variation of K_I with crack depth

The fracture toughness, K_{Ic} , of ASTM A302B may be determined using Table 8.2. A fairly typical heat treatment, such as that of note (b) in the table will be assumed. No values are available for T-S orientation, but upon examination of the table, only minor variations in K_{Ic} with different orientations are observed. Thus, two values of $(K_{Ic})_{mean}$ at -130°C (-200°F) may be chosen, the lowest of which is $33 \text{ MN/m}^{3/2}$ ($30\,030 \text{ lbf/in}^{3/2}$).

A further factor for consideration is the rate of change of fracture toughness with temperature, a high rate near the operating temperature being undesirable. It can be seen however, on referring to Sketch 7.1, that for ASTM A302B the rate of change is reasonably steady in the region of -130°C .

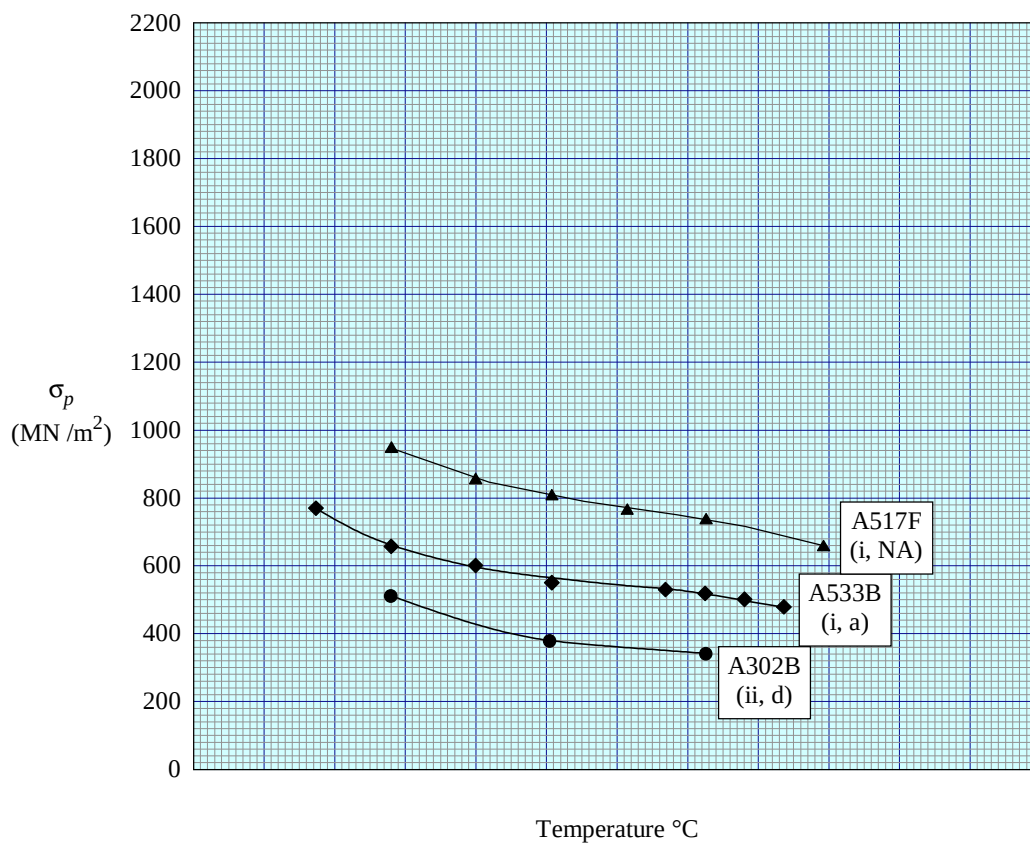
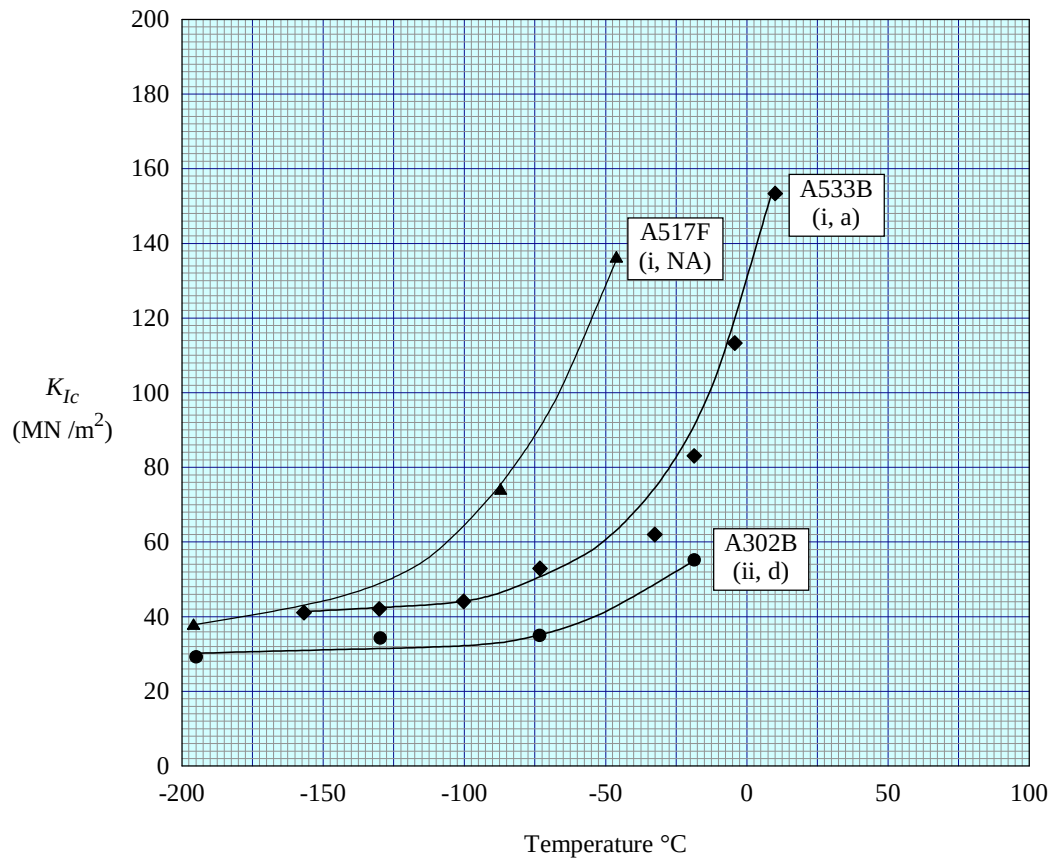
A suitable design value is obtained using Section 4.3. For a probability of 99 per cent that the actual value of K_{Ic} will exceed the allowable value calculated below, with a confidence level of 95 per cent, a value of

$k_2 = 0.6$ is obtained from Figure 4.2. Substituting the values of $(K_{Ic})_{mean}$ and k_2 into Equation (4.2) gives

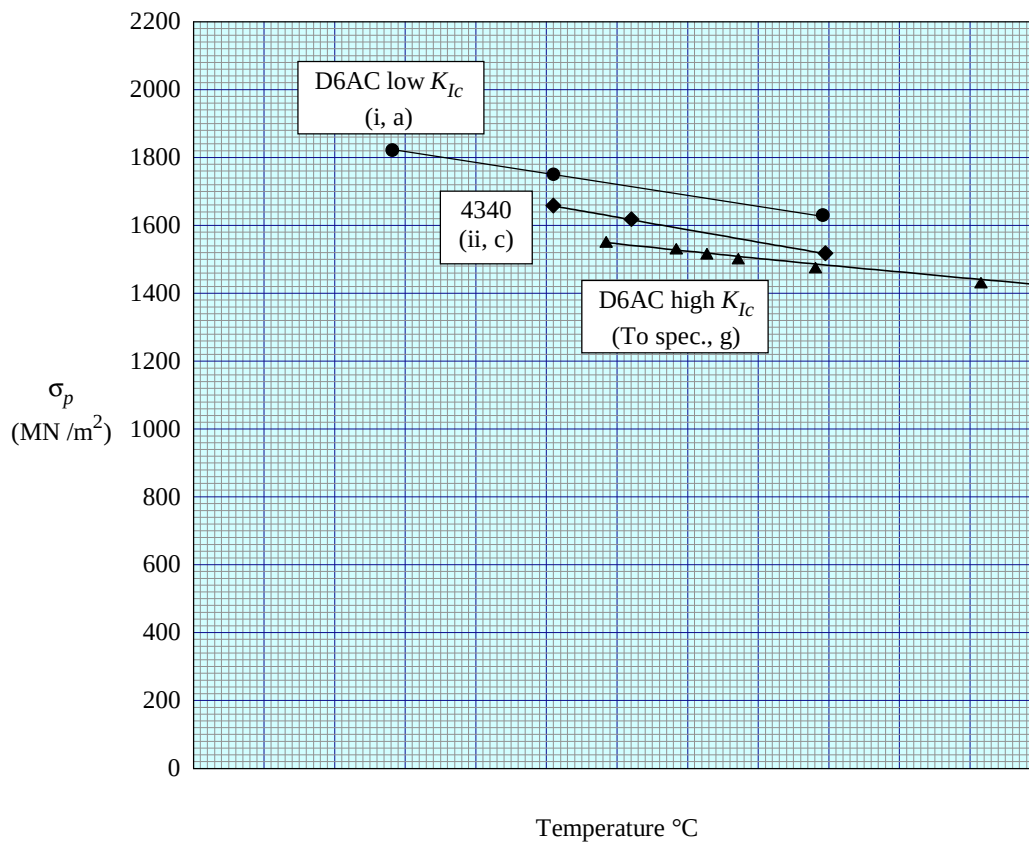
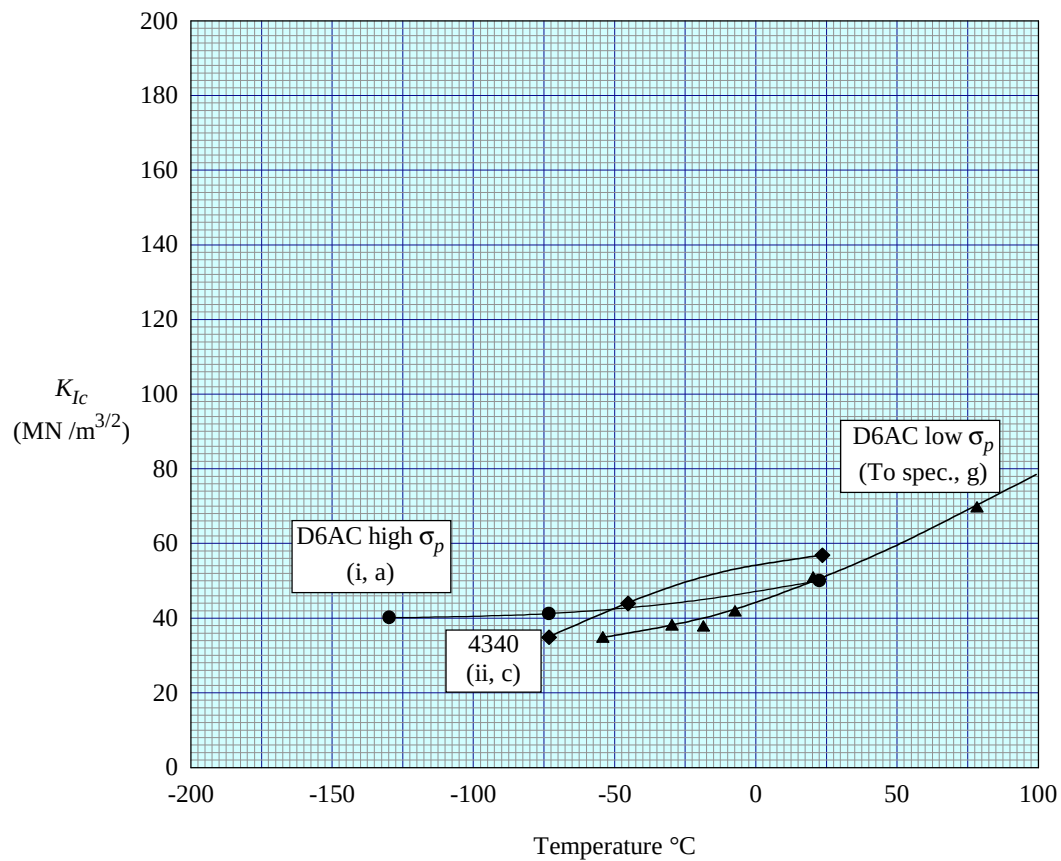
$$K_{Ic} = 0.6 \times 33 = 19.8 \text{ MN/m}^{3/2} \text{ (or } 18\,020 \text{ lbf/in}^{3/2}\text{)}.$$

The mean value of K_{Ic} and the allowable value are shown in Sketch 6.2. As may be seen the critical crack depth occurs at just under 4 mm (0.16 in). Such a crack should be detected by routine non-destructive examination well before it reaches this depth which means that the material should be quite suitable for this purpose with regard to this particular crack configuration.

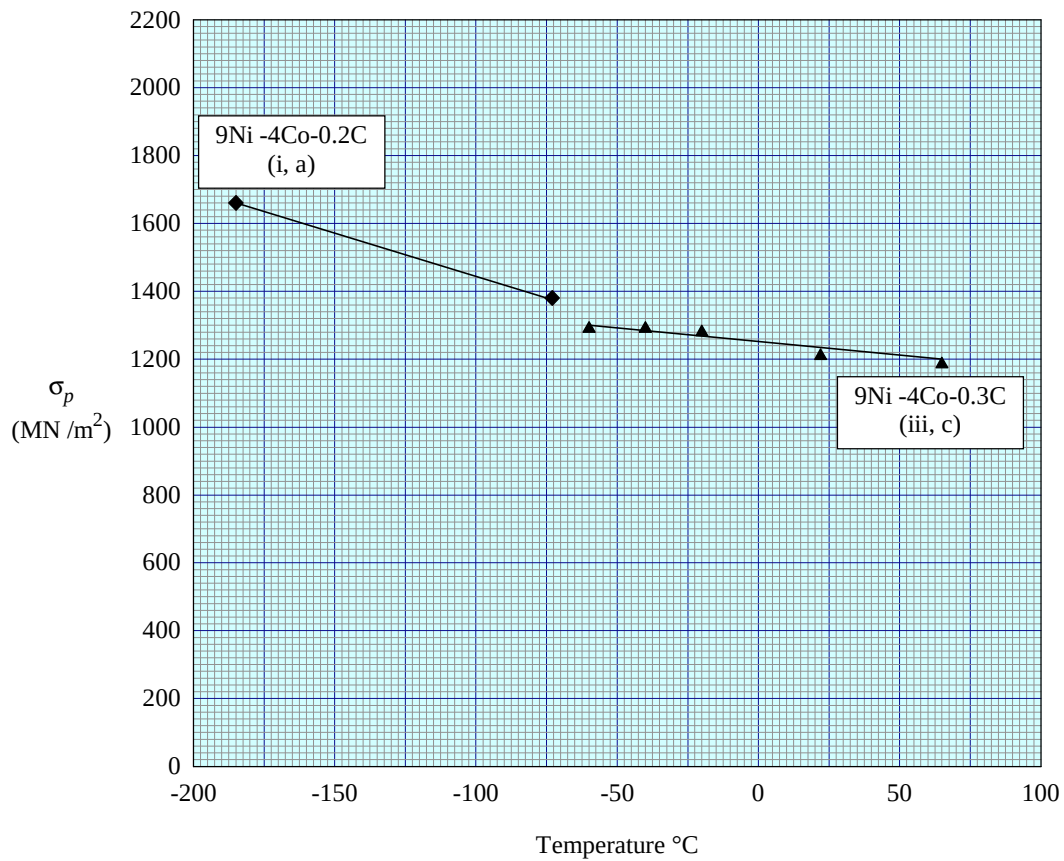
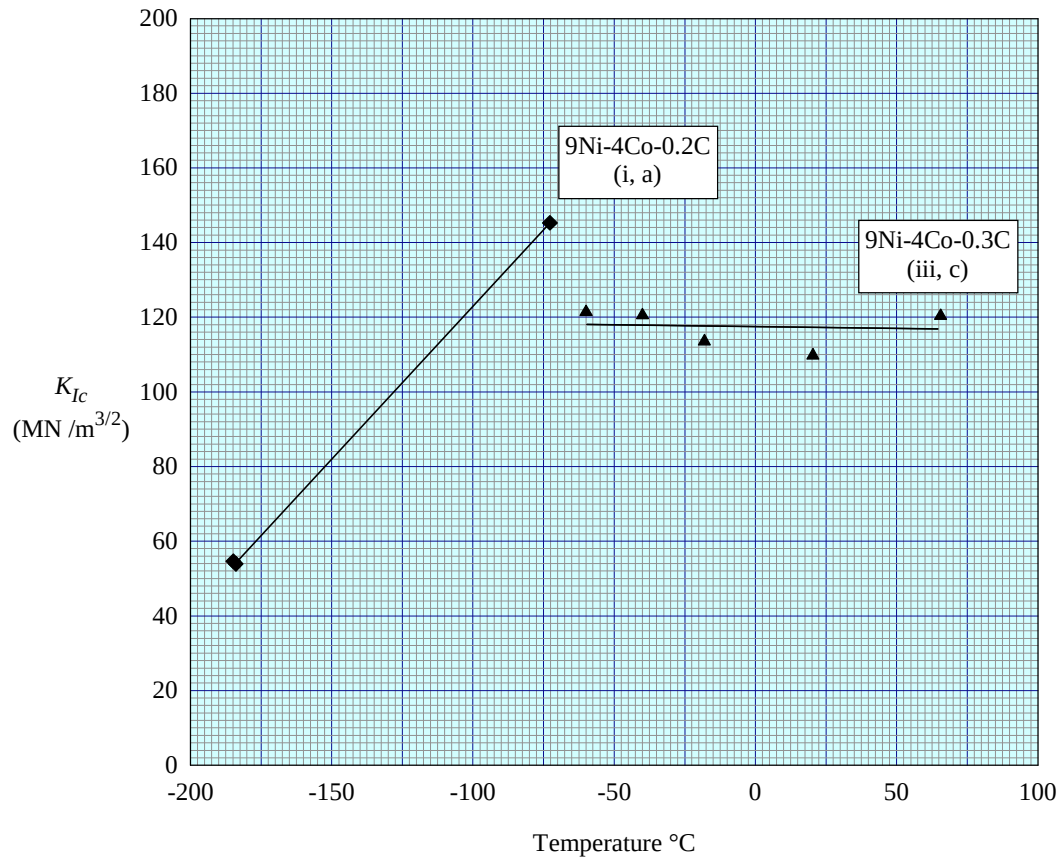
7. GRAPHS OF TEMPERATURE DEPENDENCE OF K_{Ic} AND σ_p



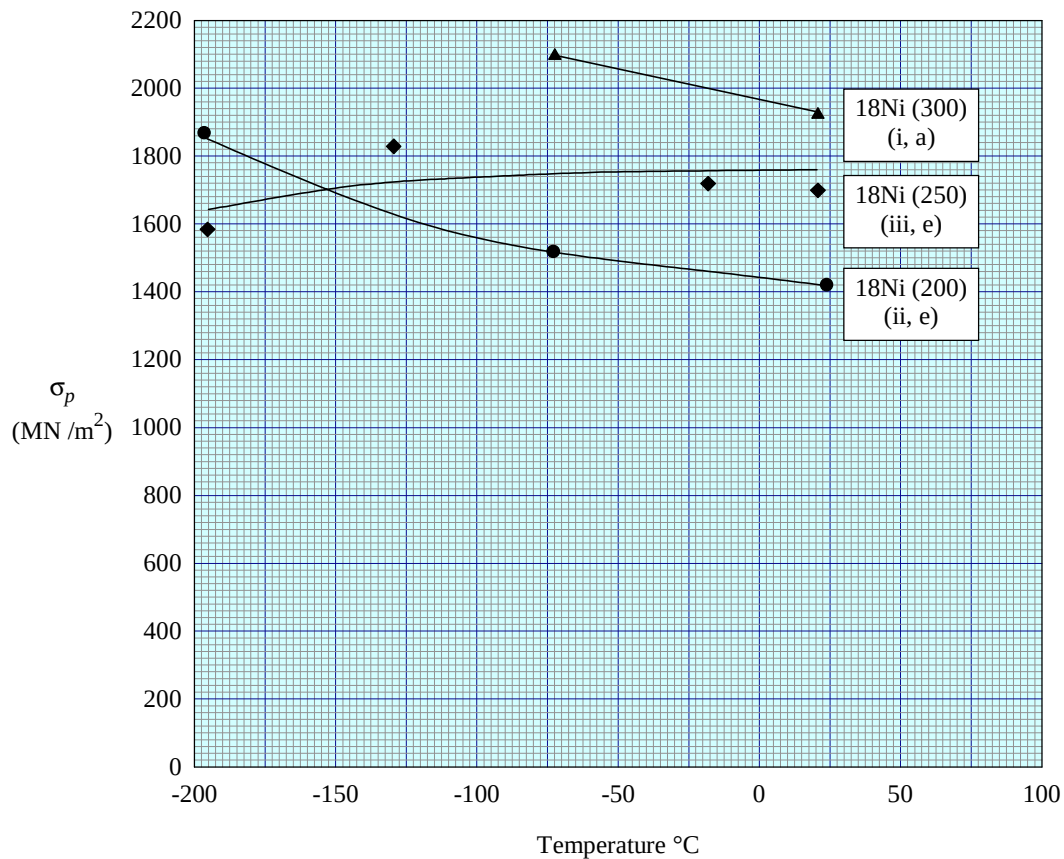
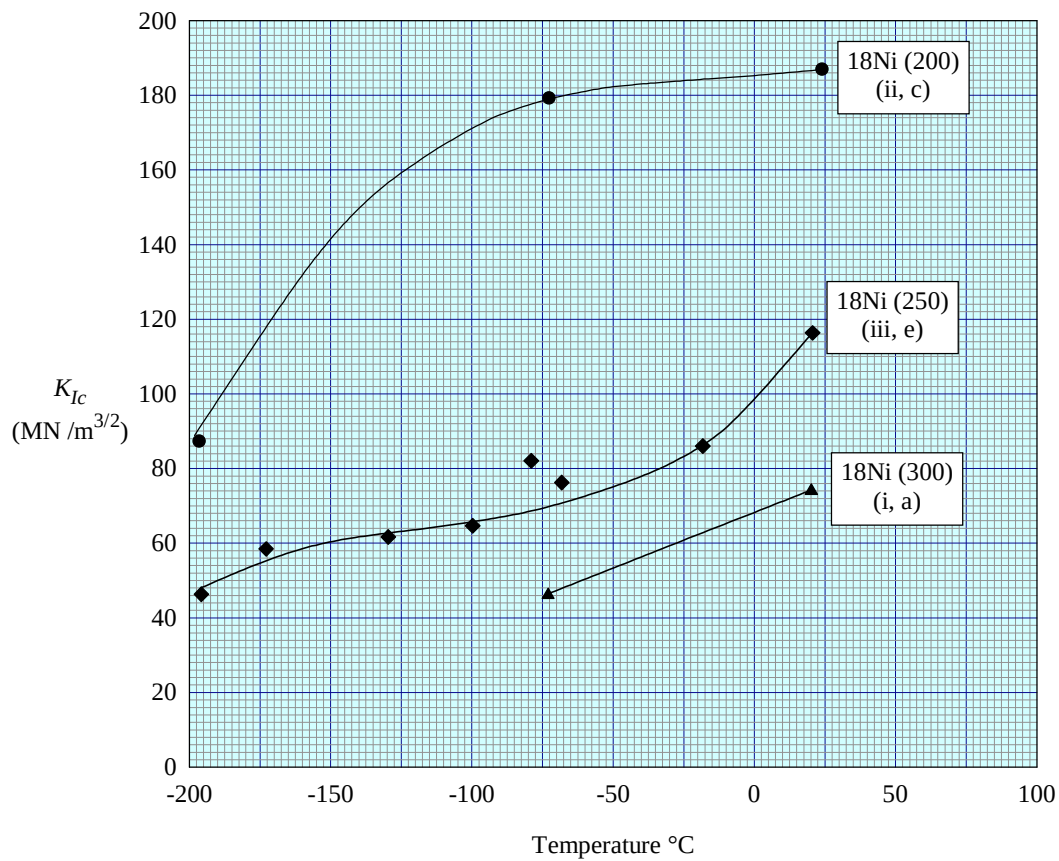
Sketch 7.1 Low alloy low strength steels. See Tables 8.1 – 8.2



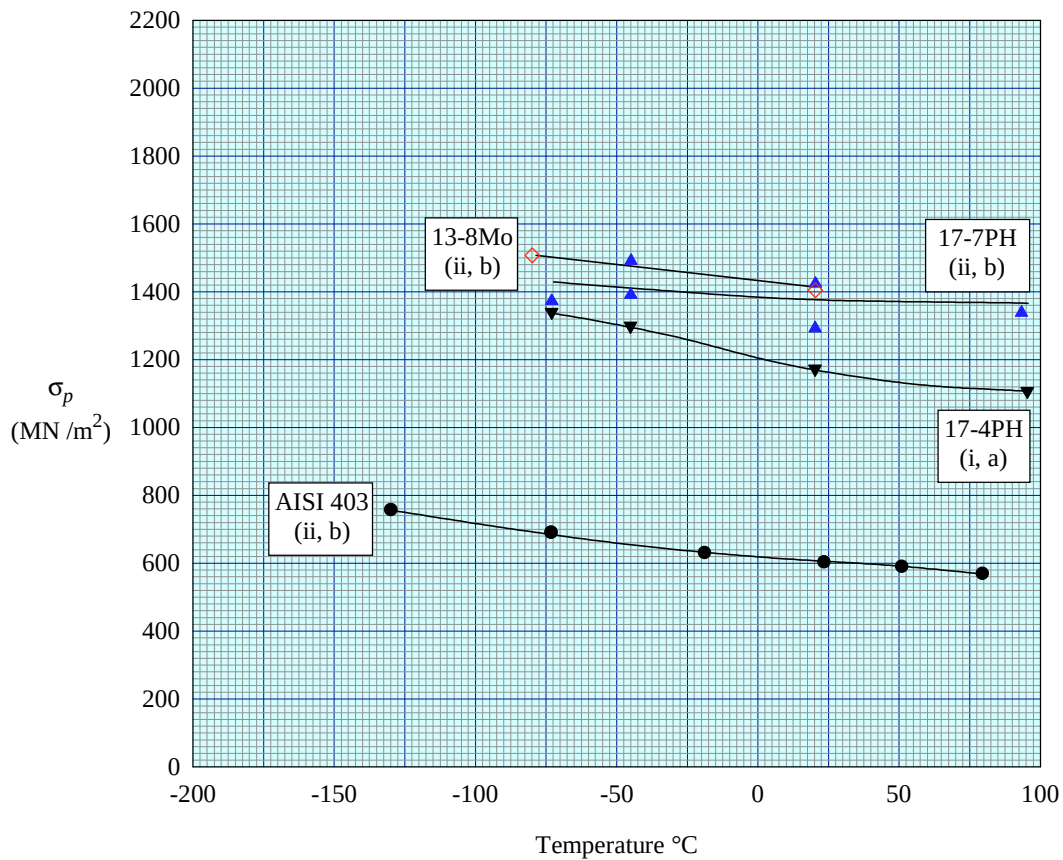
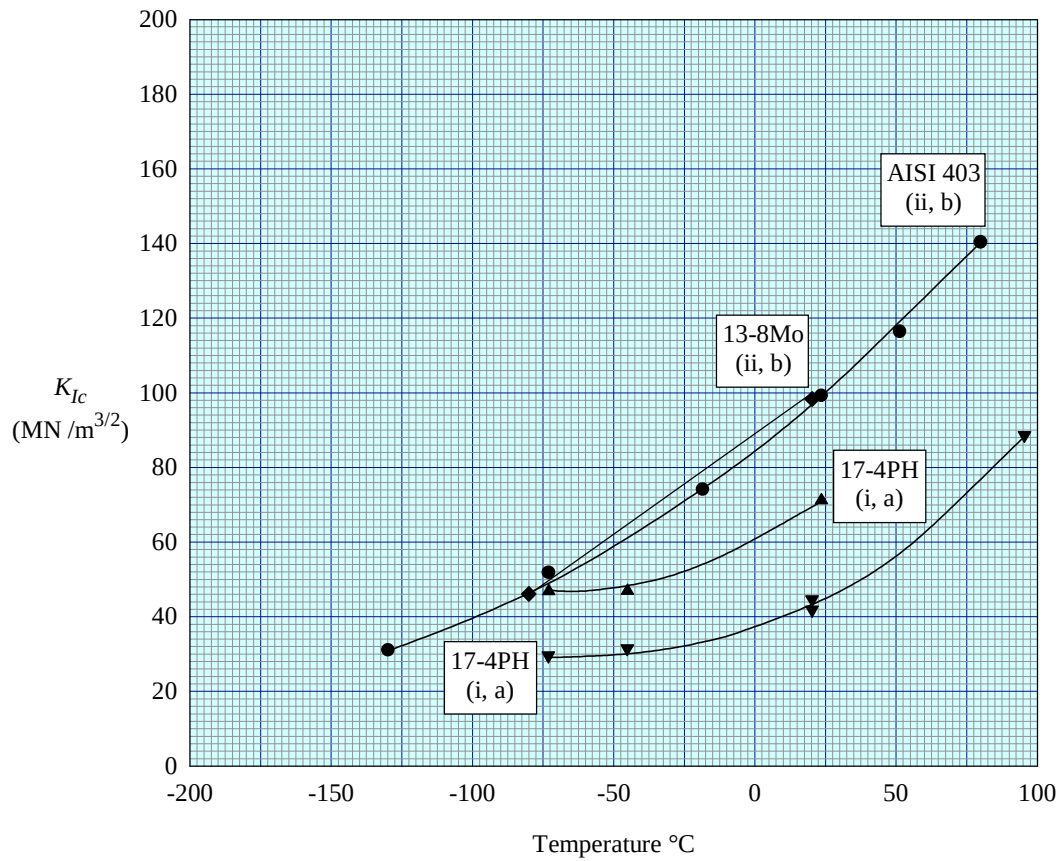
Sketch 7.2 Low alloy high strength steels. See Tables 8.13 and 8.14



Sketch 7.3 Nickel steels. See Tables 8.27 and 8.29



Sketch 7.4 Maraging steels. See Tables 8.30 – 8.32



Sketch 7.5 Stainless steels. See Tables 8.34 – 8.37

8. TABLES OF PLANE STRAIN FRACTURE TOUGHNESS VALUES**8.1 Low alloy, low strength steels**

(Tensile strength < 850 MN/m² (120 000 lbf/in²) and less than 5 per cent of any particular alloying element)

ASTM A533B	8.1
ASTM A302B	8.2
ASTM A517F	8.3
ASTM A508 Classes 2 and 3	8.4
ASTM A469 Class 2	8.5
ASTM A470 Classes 6 and 8	8.6
ASTM A217 (WC9)	8.7
BS 4360 50D	8.8
10Mn–Ni–2Mo	8.9
Cr–Ni–Mo–V	8.10
ASTM A542	8.11
ASTM A543	8.12

8.2 Low alloy, high strength steels

(Tensile strength > 850 MN/m² (120 000 lbf/in²) and less than 5 per cent of any particular alloying element.)

AISI 4340	8.13
D6AC	8.14
AISI 4330 M and V	8.15
BS970: 817M40 (En24)	8.16
BS970: 835M30 (En30B)	8.17
BS970: 897M39 (En40C)	8.18
AISI 4130	8.19
HY 130	8.20
ASTM A471	8.21
Ni–Mo–V	8.22
AISI 4140	8.23
HY-TUF	8.24
300 M	8.25
AF1410	8.26

8.3 Nickel steels

HP 9-4-20 (9Ni–4Co–0.2C)	8.27
HP 9-4-25 (9Ni–4Co–0.25C)	8.28
HP 9-4-30 (9Ni–4Co–0.3C)	8.29

8.4 Maraging steels

18Ni (200)	8.30
18Ni (250)	8.31
18Ni (300)	8.32

8.5 Stainless steels

PH 15-7 Mo	8.33
PH 13-8 Mo	8.34
17-4 PH	8.35
17-7 PH	8.36
AISI 403	8.37
15-5 PH	8.38
Custom 455	8.39

8.6 Abbreviations Used in Tables

ABQ	Aus-bay quench	LQ	Lead quench
AC	Air cool	N	Normalise
AISI	American Iron and Steel Institution	NA	Not available
AM	Air melted	OQ	Oil quench
An	Anneal	PH	Precipitation hardened
ASTM	American Society for Testing and Materials	RC	Rockwell
Au	Austenitise	SQ	Salt quench
BS	British Standard	SR	Stress relieve
CC	Controlled cool	T	Temper
CEVR	Consumable-electrode vacuum remelted	Tr	Transform
DG	Degassed	VAR	Vacuum arc remelted
ESR	Electro-slag refined	VM	Vacuum melted
FaC	Fan cool	VT	Vacuum temper
Fu	Furnace	WC	Water cool
FuC	Furnace cool	WQ	Water quench
h	Hours	WSQ	Water spray quench
QIBLN	Quench in ice brine cooled by liquid nitrogen		

8.7 Notes on Presentation of Data

Full details of the way in which the data are presented are given in Section 2.3. There are, however, four notable points regarding the presentation of the data and these are restated below.

1. The fracture toughness values in italics in Table 8.1 are values that have been derived from J_{Ic} values using Equation (2.1).
2. Where two values of thickness appear in the column headed "Form and thickness" the first value refers to the thickness of the test specimen while the second value refers to the thickness of the product from which the test specimen was taken. A single value in the column refers to the thickness of the test specimen.
3. For some of the materials in the tables only room temperature values of proof stress were available and it was these values that were used to ascertain whether or not the ASTM/BSI thickness stipulation had been met. In some such cases two numbers appear in the column headed "No. of tests", the first of which refers to the test specimens which met the thickness requirement. The second number refers to the specimens which narrowly missed the thickness requirement but which might have been found to meet it had more accurate values of proof stress for the temperatures at which the tests were conducted been available.
4. A cross in the columns headed "No. of tests" indicates data used in the statistical analysis of Section 4.3.

TABLE 8.1 ASTM A533B LOW ALLOY LOW STRENGTH STEEL (see Sketches 7.1)

Material Ref. (see table below)	Form and thick- ness mm (in)	Heat treat- ment (see below)	Orien- tation	SI Units					British Units					No. of tests	Deri- vation No.						
				Temp- erature °C	σ_p MN/m ²	$K_{Ic}^{\dagger}$ MN/m ^{3/2}			Temp- erature °F	σ_p 10 ³ lbf/in ²	$K_{Ic}^{\dagger}$ 10 ³ lbf/in ^{3/2}										
						min.	mean	max.			min.	mean	max.								
i	Plate 25-305, 305 (1-12, 12)	a	L-T	10	483	NA	153	NA	50	70	NA	140	NA	NA	15						
				-4	503		115		25	73		105									
				-18	517		83		0	75		75									
				-32	531		62		-25	77		57									
				-73	545		53		-100	79		48									
				-101	593		44		-150	86		40									
				-129	655		42		-200	95		38									
				-157	758		41		-250	110		37									
ii	Plate 51 (2)	b	L-T	-101	503	40	43	46	-150	73	36	39	42	2	2						
				-129	586	31	31	32	-200	85	28	28	29	2							
				-157	676	33	36	40	-250	98	30	33	36	2							
				-196	876	—	37	—	-320	127	—	34	—	1							
	Plate 102 (4)			-73	469	60	67	75	-100	68	55	61	68	2							
				-101	503	59	60	60	-150	73	54	54	55	2							
				-129	586	—	36	—	-200	85	—	33	—	1							
				-157	676	30	32	35	-250	98	27	29	32	2							
				-196	876	—	29	—	-320	127	—	26	—	1							
				iii	Plate 25-102, 300 (1-4, 11.8)	c	L-T	-18	531	NA	95	NA	0	77		NA	86	NA	NA	15	
								-46	565		82		-50	82			75				
								-73	586		60		-100	85			55				
								-129	655		49		-200	95			45				
								-196	965		42		-320	140			38				
iv	25 (1)	NA	NA					-65	475 [‡]	—	46	—	-85	69 [‡]	—	42	—	1 ⁺			31
								-85		—	38	—	-121		—	35	—	1 ⁺			
	40 (1.6)							-65		52	58	67	-85		47	52	61	4/1 ⁺			
								-75		49	59	66	-103		45	53	60	3/1			
				-85	45	56	68	-121		41	51	62	6/3 ⁺								
	80 (3.1)			-65	63	77	89	-85		57	70	81	8/2 ⁺								
				-65	79	89	98	-85		72	81	89	5 ⁺								
	127 (5)																				

HEAT TREATMENT NOTES

(a) N 913 °C (1675 °F), Au 871 °C (1600 °F) 4h, WQ, T 663 °C (1225 °F) 4h, FuC, SR 621 °C (1150 °F) 40h, AC

(b) Au 899 °C (1650 °F) 1h, T 649 °C (1200 °F) 8h, SR 593 °C (1100 °F) 24h

(c) N 913 °C (1675 °F), Au 871 °C (1600 °F) 4h, WQ, T 663 °C (1225 °F) 4h, AC, SR 613 °C (1135 °F) 25h, FuC to 316 °C (600 °F), AC

Material reference	Chemical analysis of alloying elements by weight (per cent)											
	C	Si	Mn	Ni	Cr	Mo	S	P	V	Al	Ti	Other
Specification	0 0.25	0.13 0.45	1.07 1.62	0.37 0.73		0.41 0.64	0 0.040	0 0.035				
(i)	0.24	0.22	1.42	0.70		0.50	0.017	0.010				
(ii)	0.18	0.24	1.25	0.52	0.13	0.51	0.025	0.024		0.025		Cu-0.29
(iii)	0.23	0.26	1.35	0.50		0.48	0.025	0.012				
(iv)	0.19	0.21	1.20	0.68	0.03	0.49	0.013	0.017				Cu-0.07

[†] The K_{Ic} values in italics are derived from J_{Ic} values using the method detailed in Section 2.1.[‡] Room temperature value.⁺ These data are included in the statistical analysis in Section 4.3.

TABLE 8.1 (Continued) ASTM A533B LOW ALLOY LOW STRENGTH STEEL (see Sketches 7.1)

Mat- erial Ref. (see table below)	Form and thick- ness mm (in)	Heat treat- ment (see below)	Orien- tation	SI Units					British Units					No. of tests	Deri- vation No.	
				Temp- erature °C	σ_p MN/m ²	$K_{Ic}^{\dagger}$ MN/m ^{3/2}			Temp- erature °F	σ_p 10 ³ lbf/in ²	$K_{Ic}^{\dagger}$ 10 ³ lbf/in ^{3/2}					
						min.	mean	max.			min.	mean	max.			
v	Plate 13 (0.5)	e	L-T	-150	444 [†]	27	32	36	-238	64 [†]	25	29	33	4/4 ⁺	30	
	-75 -150			-		35 34	-	41 49	-103 -238		-	32 31	-	45		1 ⁺ 11/3 ⁺
	-75 -150			60 32		64 43	68 58	-103 -238	54 29		58 40	62 52	1/1 ⁺ 11/1 ⁺			
	-75			58		79	99	-103	52		71	90	3/2 ⁺			

HEAT TREATMENT NOTES

(e) T 893 °C (1639 °F) 7.5h, WQ, T 671 °C (1240 °F) 8.5h, WQ, T 565 °C (1049 °F) 4h, AC, T 621 °C (1150 °F) 50h,
FuC to 316 °C (600 °F)

Material reference	Chemical analysis of alloying elements by weight (per cent)											
	C	Si	Mn	Ni	Cr	Mo	S	P	V	Al	Ti	Other
Specification	0 0.25	0.13 0.45	1.07 1.62	0.37 0.73		0.41 0.64	0 0.040	0 0.035				
(v)	0.19	0.21	1.28	0.64		0.55	0.013	0.012				

[†] The K_{Ic} values in *italics* are derived from J_{Ic} values using the method detailed in Section 2.1.

[‡] Room temperature value.

⁺ These data are included in the statistical analysis in Section 4.3.

TABLE 8.2 ASTM A302B LOW ALLOY LOW STRENGTH STEEL (see Sketches 7.1)

Material Ref. (see table below)	Form and thick- ness mm (in)	Heat treat- ment (see below)	Orien- tation	SI Units					British Units					No. of tests	Deri- vation No.
				Temp- erature °C	σ_p MN/m ²	K_{Ic} MN/m ^{3/2}			Temp- erature °F	σ_p 10 ³ lbf/in ²	K_{Ic} 10 ³ lbf/in ^{3/2}				
						min.	mean	max.			min.	mean	max.		
i	Plate 25 (1)	a	L-T	-101 -129 -157 -196	450 500 610 850	NA 36 24 23	52* 36 30 27	NA 36 37 31	-150 -200 -250 -320	65 73 89 123	NA 33 22 21	47* 33 27 25	NA 33 34 28	NA 2 3 2	7
ii	Plate 25-102, 178 (1-4, 7)	b	T-L	-18 -73 -129 -196	350 430 590 970	36 35 24 24	49 42 34 32	53 45 47 43	0 -100 -200 -320	50 63 85 140	33 32 22 22	45 38 31 29	48 41 43 39	3 3 13 ⁺ 7	3
iii	Plate 25-152, 178 (1-6, 7)	c	L-T	-32 -129 -157	420 570 680	NA	83 46 34	NA	-25 -200 -250	61 82 98	NA	76 42 31	NA	NA	15
iv	Plate 51-102, 178 (2-4, 7)	b	L-T	-73 -129 -196	410 550 900	NA	44 33 30	NA	-100 -200 -320	60 80 130	NA	40 30 27	NA	NA	15
ii	Plate 25-102, 178 (1-4, 7)	d	T-L	-18 -73 -129 -196	340 380 510 NA	54 27 25 25	55 35 34 29	59 43 42 31	0 -100 -200 -320	49 55 74 NA	49 25 23 23	50 32 31 26	54 39 38 28	2 3 9 ⁺ 4	3
ii	Plate 10, 175 (0.4, 7)	e	L-T	-112 -196	517 752	56 25	59 27	62 29	-170 -320	75 109	51 23	54 25	56 26	2 2	1
	-70 -96			462 490	- -	75 47	- -	-94 -141	67 71	- -	68 43	- -	1 1		

HEAT TREATMENT NOTES

- (a) 899 °C (1650 °F) 12h, AC
 (b) N 899 °C (1650 °F) 7h, FaC to 93 °C (200 °F), AC, SR 649 °C (1200 °F) 7h
 (c) 899 °C (1650 °F) 7h, SR 650 °C (1200 °F), FaC to 93 °C (200 °F), AC
 (d) 1246 °C (2275 °F) 2h, FaC at 38 °C (100 °F) per h to 496 °C (925 °F), AC
 (e) Au 899 °C (1650 °F), AC, SR 649 °C (1200 °F)

Material reference	Chemical analysis of alloying elements by weight (per cent)											
	C	Si	Mn	Ni	Cr	Mo	S	P	V	Al	Ti	Other
Specification	0 0.20	0.13 0.45	1.07 1.62			0.41 0.64	0 0.040	0 0.035				
(i)	0.19	0.16	1.40	0.03	0.07	0.49	0.014	0.017		0.010		Cu-0.03
(ii)	0.21	0.27	1.34	0.04		0.50	0.010	0.015				
(iii)	0.21	0.34	1.35	0.16	0.21	0.33	0.014	0.013				Cu-0.005
(iv)	0.21	0.27	1.54	0.04		0.50	0.010	0.015				

* ASTM/BSI thickness stipulation not quite met. See Section 2.2.

+ These data are included in the statistical analysis in Section 4.3.

TABLE 8.2 (Continued) ASTM A302B LOW ALLOY LOW STRENGTH STEEL (see Sketches 7.1)

Material Ref. (see table below)	Form and thick- ness mm (in)	Heat treat- ment (see below)	Orien- tation	SI Units					British Units					No. of tests	Deri- vation No.
				Temp- erature °C	σ_p MN/m ²	K_{Ic} MN/m ^{3/2}			Temp- erature °F	σ_p 10 ³ lbf/in ²	K_{Ic} 10 ³ lbf/in ^{3/2}				
						min.	mean	max.			min.	mean	max.		
v	Plate 3 (0.1)	f	L-T	-129	648	76	79	84	-200	94	69	72	76	2	1
				-157	758	51	59	68	-250	110	46	54	62	2	
				-196	1062	48	51	56	-320	154	44	46	51	3	
	Plate 10 (0.4)			-146	710	40	46	53	-230	103	36	42	48	2	
				-196	1062	24	29	35	-320	154	22	27	32	3	
				Plate 76 (3)	-70	531	—	134	—	-94	77	—	122	—	
	-139				683	—	55	—	-218	99	—	50	—	1	
	-196				1062	—	47	—	-320	154	—	43	—	1	
	NA			Plate —, 230 (—, 9)	g	NA	25	390	—	98	—	77	56	—	
0		400	—				77	—	32	58	—	70	—		
-101		540	—				49	—	-150	78	—	45	—		
-196		NA	—				47	—	-320	NA	—	43	—		
As above HAZ	Plate —, 230 (—, 9)	g	NA	40	500	—	80	—	104	73	—	73	—	20	8
				0	530	—	47	—	32	77	—	43	—		
				-50	580	—	41	—	-58	84	—	37	—		

HEAT TREATMENT NOTES

(f) Au 949 °C (1740 °F), WQ, T 649 °C (1200 °F)

(g) 888 °C (1630 °F) 8h, 677 °C (1250 °F), FuC for 12h to 249 °C (480 °F)

Material reference	Chemical analysis of alloying elements by weight (per cent)											
	C	Si	Mn	Ni	Cr	Mo	S	P	V	Al	Ti	Other
Specification	0 0.20	0.13 0.45	1.07 1.62			0.41 0.64	0 0.040	0 0.035				
(v)	0.20	0.22	1.15			0.50	0.27	0.015				

TABLE 8.3 ASTM A517F LOW ALLOY LOW STRENGTH STEEL (see Sketches 7.1)

Material Ref. (see table below)	Form and thick- ness mm (in)	Heat treat- ment (see below)	Orien- tation	SI Units					British Units					No. of tests	Deri- vation No.	
				Temp- erature °C	σ_p MN/m ²	K_{Ic} MN/m ^{3/2}			Temp- erature °F	σ_p 10 ³ lbf/in ²	K_{Ic} 10 ³ lbf/in ^{3/2}					
						min.	mean	max.			min.	mean	max.			
i	Plate 50 (2)	NA	L-T	22 -46 -87 -196	760 NA	- - - -	NA 136 74 38	- - - -	72 -51 -125 -320	110 NA	- - - -	NA 124 67 35	- - - -	} 33	14	
ii	Plate 25, 25 (1, 1)	NA	NA	22 -73 -90 -112 -129 -157 -196	390 NA	NA 75 - 55 53 43 38	NA NA 79 68 58 53 45 40	NA NA 82 - 61 53 47 41	72 -100 -130 -170 -200 -250 -320	56 NA	NA 68 - 50 48 39 35	NA NA 72 62 53 48 41 36	NA 75 - 56 48 43 37		- 4 1 2 3 3 3	7
iii	Plate 50 (2)	NA	NA	24 -18 -46 -73 -101 -129	660 740 770 810 860 950	NA NA NA NA NA NA	NA 123* 96 77 64 52	NA NA NA NA NA NA	75 0 -50 -100 -150 -200	95 107 111 117 124 138	NA NA NA NA NA NA	NA 112* 87 70 58 47	NA NA NA NA NA NA		NA NA NA NA NA NA	5
iv	Plate	NA	NA	24	760	176*	187*	195*	75	110	160*	170*	177*		NA	6

HEAT TREATMENT NOTES

Material reference	Chemical analysis of alloying elements by weight (per cent)											
	C	Si	Mn	Ni	Cr	Mo	S	P	V	Al	Cu	Other
Specification	0.10	0.15	0.60	0.70	0.40	0.40	0	0	0.03		0.15	B-0.002
	0.20	0.35	1.00	1.00	0.65	0.60	0.040	0.035	0.08		0.50	B-0.006
(i)	0.17	0.19	0.89	0.84	0.52	0.42	0.015	0.015	0.040	0.035	0.30	B-0.003
(ii)	0.17	0.23	0.78	0.88	0.56	0.42	0.017	0.012	0.036		0.26	B-0.003
(iii)	0.17	0.24	0.78	0.89	0.55	0.43	0.017	0.012	0.036		0.26	
(iv)	0.16	0.23	0.79	0.87	0.53		0.016	0.010				

* ASTM/BSI thickness stipulation not quite met. See Section 2.2.

TABLE 8.4 ASTM A508 CLASSES 2 AND 3 LOW ALLOY LOW STRENGTH STEELS

Material Ref. (see table below)	Form and thick- ness mm (in)	Heat treat- ment (see below)	Orien- tation	SI Units					British Units					No. of tests	Deri- vation No.
				Temp- erature °C	σ_p MN/m ²	K_{Ic} MN/m ^{3/2}			Temp- erature °F	σ_p 10 ³ lbf/in ²	K_{Ic} 10 ³ lbf/in ^{3/2}				
						min.	mean	max.			min.	mean	max.		
i Class 2	Cylinder 25 (1)	a	T-S	-18 -73	521 574	51 39	52 45	53 54	0 -100	76 83	46 35	47 41	48 49	2 5	33
	Cylinder 102 (4)	b	T-S	-10 -18	NA 521	- 54	63 66	- 77	14 0	NA 76	- 49	57 60	- 70	1 4	
ii Class 3	Forging Plate 25 (1)	c	L-T	-101 -150	580 680	- 44	59 49	- 53	-150 -238	84 99	- 40	54 44	- 48	1 2	28
NA	10 (0.4)	d	NA	-45	741	-	41	-	-50	107	-	37	-	1	28
	25 (1)			32	689	-	70	-	90	100	-	64	-	0/1	
	10			702	-	72	-	50	102	-	66	-	0/1		
	-32			731	-	49	-	-25	106	-	45	-	1		
	-45			741	-	46	-	-50	107	-	42	-	1		
	-73			763	38	55	72	-100	111	35	50	66	1		
51 (2)	-18	719	-	51	-	0	104	-	46	-	1				

HEAT TREATMENT NOTES

- (a) N 888 °C (1630 °F) 9h, Au 861 °C (1582 °F) 7h, WQ, VT 621 °C (1150 °F) 7h
 (b) N 888 °C (1630 °F) 9h, Au 861 °C (1582 °F) 7h, WQ, VT 621 °C (1150 °F) 10h
 (c) Au 890 °C (1634 °F) 6.5h, WQ, T 660 °C (1220 °F) 10.5h, AC, SR 550 °C (1022 °F) 55h, FuC, SR 600 °C (1112 °F) 20.5h, FuC, SR 600 °C (1112 °F) 10.5h, FuC
 (d) T 613 °C (1135 °F)

Material reference	Chemical analysis of alloying elements by weight (per cent)											
	C	Si	Mn	Ni	Cr	Mo	S	P	V	Al	Ti	Other
Class 2 Spec.	0 0.27	0.15 0.40	0.50 1.00	0.50 1.00	0.25 0.45	0.55 0.70	0 0.015	0 0.012	0 0.050			
Class 3 Spec.	0 0.25	0.15 0.40	1.20 1.50	0.40 1.00	0 0.25	0.45 0.60	0 0.025	0 0.025	0 0.050			
(i)	0.21	0.24	0.57	0.74	0.35	0.66	0.012	0.007	<0.01			
(ii)	0.21	0.29	1.36	0.64	0.19	0.52	0.004	0.009	<0.01			