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Assessment of the fracture toughness of cast steels

Part 2 *Carbon and carbon manganese steels*

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Two plain carbon and a carbon manganese steel were tested to determine K_C or K_{IC} values. Test methods employed were linear elastic fracture mechanics, LEFM, *J*-integral, and crack opening displacement, COD. The latter two methods were applied in combination with direct determination of crack initiation by the electrical potential method. The LEFM method appeared to give K_C values, but in fact the load/COD curve deviation from linearity was shown to arise from a sudden onset of plasticity rather than from fracture. *J*-integral analysis showed toughnesses to be far in excess of the K_Q values.

1. Introduction

Plain carbon and carbon manganese steels are used extensively in the steel castings industry. They are of high toughness yet controlled by concepts of defect tolerance generally applicable to higher strength steels which are often more brittle. The work described here was part of a larger programme to survey the fracture toughness of typical cast steels, some of the other work being described in Part 1 [1].

As in Part 1 the basic specimen size chosen for the survey was 45 mm wide, W, 25 mm thickness, B, and specimens were tested in three-point bending with a span between loading points of $4W$. The material was taken from regions of cast keel blocks shown to be free of casting defects by radiography. Six specimens of this size were sawn from each keel block, the heat-treatments described below being carried out on the block before cutting up.

Fig. 1 compares the fracture loads, P_Q, which satisfy specifications for K_{IC} testing [2], with the general yield loads, P_{GY}, in terms of P_{GY}/BW versus $\sigma_Y B^{1/2}$ and (see Part 1):

$$\frac{P_{GY}}{BW} = \frac{1.25\sigma_Y}{4}\left(1 - \frac{a}{W}\right)^2. \qquad (1)$$

The points inserted for the steels code named D, L and A, indicate general yield loads for the size of specimen described above with notch length, a, such that $a/W = 0.5$. The maximum constraint factor of 1.25 for this kind of notch is used [3, 4].

In order to satisfy the requirements for a K_{IC} test, it appears that the fracture load P_Q should be around $P_{GY}/2$. However, if the fracture load is less than $0.8P_{GY}$ the test is normally such that the ligament is behaving in an approximately linear elastic manner and the K_C result expresses a toughness applicable to the thickness of metal tested. Fig. 2 shows general yield loads for the materials and specimen size used here. Average values of P_Q obtained by the 95% secant method are also indicated. It would appear that steels D and L

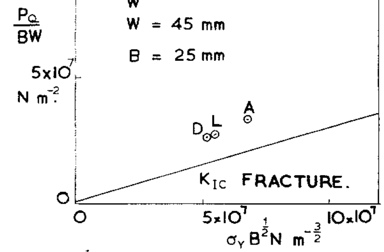

Figure 1 General yield load, P_{GY}, divided by BW for steels D, L and A plotted versus $\sigma_Y B^{1/2}$. Line shows limit of K_{IC} testing as P_Q/BW versus $\sigma_Y B^{1/2}$.

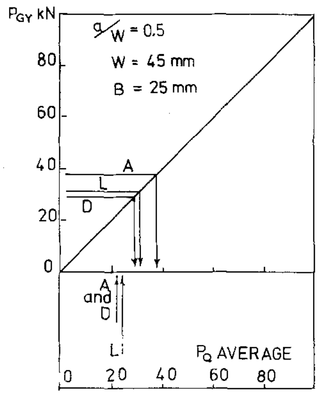

Figure 2 General yield loads compared with average P_Q measured for steels D, L and A.

should be near to approximate linear elastic behaviour.

In fact, the P_Q values plotted in Fig. 2 are anomalous values in that although they obey the deviation from linearity condition 2, they do not correspond to fracture initiation at all, but to the sudden development of a plastic zone. An indicator of this is that they do not meet the $P_Q/P_{max} < 1.1$ condition introduced as an amendment to the testing standard and incorporated in ASTM-E399-72 [5] and proposed for BSI DD3-1972 [2].

The tests described below are all at or near to general yield, in fact, as shown by the load/COD curve taken in conjunction with detection of crack initiation by the electrical potential. Nevertheless, based on the confidence in the *J*-integral [6], and the COD methods established in Part 1, it is believed that the assessments of K_{IC} made here are reasonably accurate measures of the material toughness.

2. Experimental methods and materials

The specimen shape and manufacture, the test rigs and instrumentation were all described in Part 1. Specifications of the steels, chemical compositions, heat-treatments and tensile properties are shown in Tables I to III.

3. Results

3.1. Steel D. plain carbon

Tests on steel D gave the K_Q values showing an apparent toughness of 51 MN m$^{-3/2}$ as in Fig. 3. These tests met the elastic linearity test in that the deviation from linearity on the load/COD curve was negligible at $0.8P_Q$ as compared with that at P_Q as determined by the secant method. In spite of this the ratio P_{max}/P_Q was about 1.7 in all

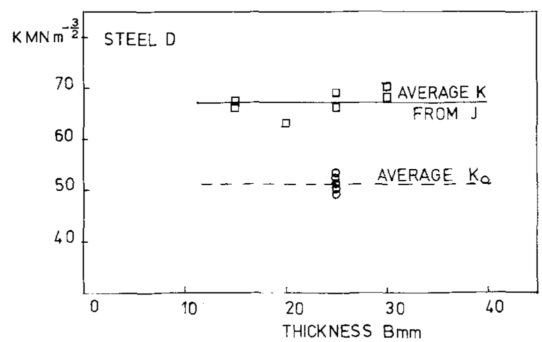

Figure 3 K_{IC} values derived from *J* at fracture initiation for steel D, compared with K_Q values corresponding to sudden yield.

TABLE I Steel specifications

Code letter	BS specification
A	BS 1456 A (1½Mn)
D	BS 592 B (plain carbon)
L	BS 1760 B (plain carbon)

TABLE II Chemical compositions of the steels

Steel	C	Si	Mn	S	P	Ni	Cr	Mo	Al	Cu	V	Sn
A	0.24	0.40	1.26	0.008	0.022							
D	0.34	0.40	0.85	0.018	0.030	0.17	0.10	0.04	0.019	0.32	0.01	–
L	0.54	0.85	1.02	0.030	0.013	0.02	0.01	0.02	0.023	–	–	–

TABLE III Heat-treatment and tensile properties

Steel	Heat-treatment	Tensile strength (MN m^{-2})	Yield stress (MN m^{-2})
A	3 h 960° C FC; 3 h 960° C AC	639.1	426.6
D	4 h 950° C FC	577.5	329.6
L	5 h 900° C FC	734.0	360.0

FC, furnace cooled; AC, air cooled.

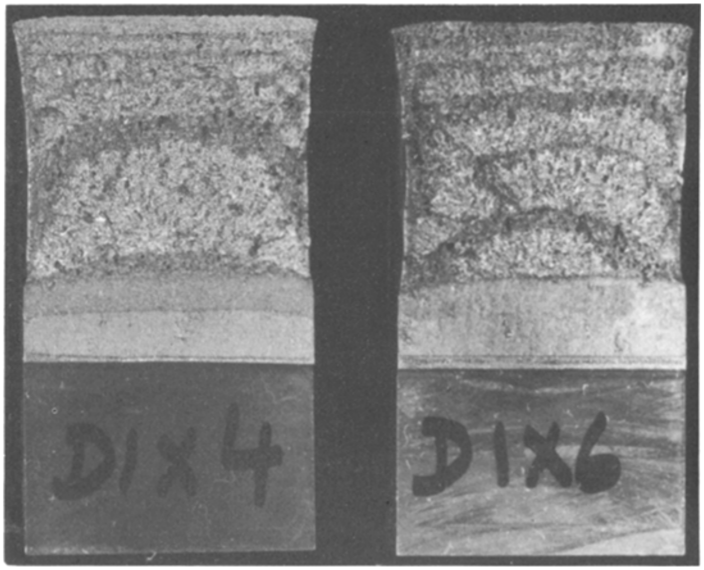

Figure 4 Fracture surfaces of 25 mm thick specimens of steel D.

cases, showing that the deviation was plastic in origin, the rise in load occurring due to work-hardening as a plastic zone began to cross the ligament. The electrical potential detection showed crack initiation well beyond P_Q. This sudden onset of plastic behaviour is akin to the sudden yielding which gives the upper and lower yield point and a Luders extension in wrought mild steels.

Fig. 3 shows the K_C derived from J-integral tests using:

$$J = \frac{2}{B(W-a)} \int_0^{\delta_{\text{crack}}} P\,\mathrm{d}(\delta_{\text{crack}}) \qquad (2)$$

and

$$K^2 = \frac{JE}{1-\nu^2} \qquad (3)$$

as described in Part 1.

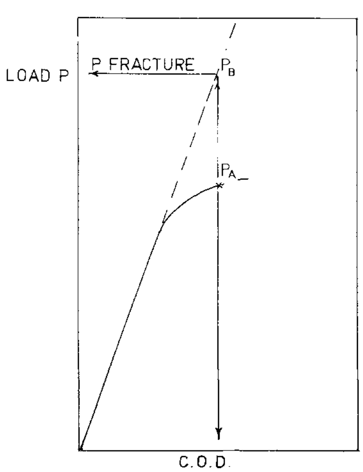

Figure 5 Schematic illustration of scaling method for K_C.

The fracture surfaces shown in Fig. 4 indicate conditions close to plane strain judging from the relatively small shear lips. The progression of cracking appears to oscillate between cleavage and fibrous fracture, probably because of repeated crack initiation and arrest.

A simpler method than the J-integral was introduced by Stonesifer *et al.* [7] to derive K_C by a scaling method for tests just beyond the limits of LEFM. Fig. 5 indicates their method. The fracture load is not taken as P_Q, but as the extrapolated linear elastic load at the fracture COD. Thus P_Q is estimated as P_B rather than P_A in Fig. 5.

The above method was experimented with on the results generated here, but the COD at fracture was detected by the electrical potential method. These results are shown in Fig. 6 upon which is superimposed the K_C from the J-integral method and the K_Q from the anomalous P_Q average for

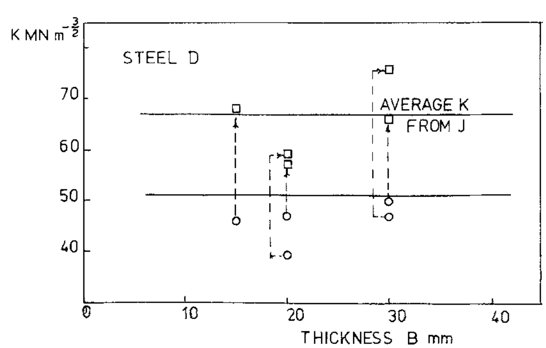

Figure 6 Squares indicate estimates of K_C using the scaling method, circles indicate K estimates from the load at the fracture COD, P_A.

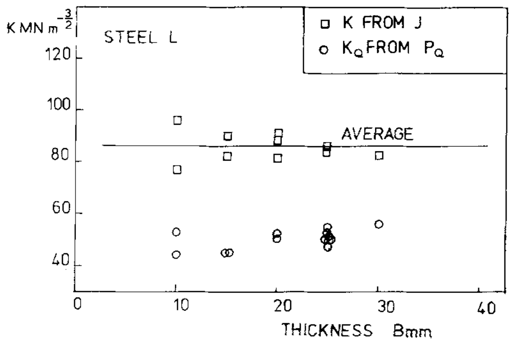

Figure 7 K_{IC} estimates from J at fracture initiation in steel L, and K_Q values corresponding to sudden yielding.

test pieces 25 mm thick. These tests were conducted on a range of thicknesses but with W constant at 45 mm as were the J-integral tests. The method does not appear to have any special advantage and is based on less rigourous concepts than the J-integral.

COD tests using the calibrated clip gauge as described in Part 1 gave V_G, clip gauge COD values, which were converted to crack tip COD, δ_t, using Equation 5 in Part 1, the linear relation derived by Wells [4, 8]. The resulting δ_t were between 0.04 mm and 0.08 mm over a thickness range of 15 to 30 mm. The results showed no significant variation of δ_t with thickness. Using a K_C value of 67 MN m$^{-3/2}$ from the J-integral results gave an average estimated value of the stress intensification value (the factor by which the yield stress is elevated by constraints) of 1.1.

3.2. Steel L, plain carbon

Steel L is a slightly higher strength plain carbon steel to steel D. Tests on the 25 mm thick specimen showed the same characteristics as those of steel D, the anomalous P_Q values again corresponding to no crack initiation and P_Q/P_{max} about 1.7 in all cases. The K_Q derived from P_Q values together with the K_{IC} derived from J-integral tests are shown in Fig. 7. All the fractures were predominantly cleavage, as shown in Fig. 8, and the lack of shear lips is consistent with plane strain fractures. The toughness derived from the J-integral tests remained at about 86 MN m$^{-3/2}$ down to a thickness of 10 mm.

Crack tip COD values, δ_t, using the linear relation between V_G and δ_t [4, 8] were in the range 0.05 to 0.09 mm. Assuming a K_{IC} of 86 MN m$^{-3/2}$ the stress intensification value, n, varied from about 1.0 at a thickness of 10 mm to 1.8 at 25 mm.

3.3. Steel A, carbon manganese

Steel A has a very high toughness but again showed the linear elastic behaviour followed by sudden development of a plastic zone. The K_Q values of around 40 to 50 shown in Fig. 9 do not correspond to crack initiation but to plastic failure. Again the ratio P_{max}/P_Q was close to 1.7 in all cases. Detection of crack initiation by the electrical potential allowed K_{IC} values to be estimated from J. These are around 140 MN m$^{-3/2}$ as shown in Fig. 9. These

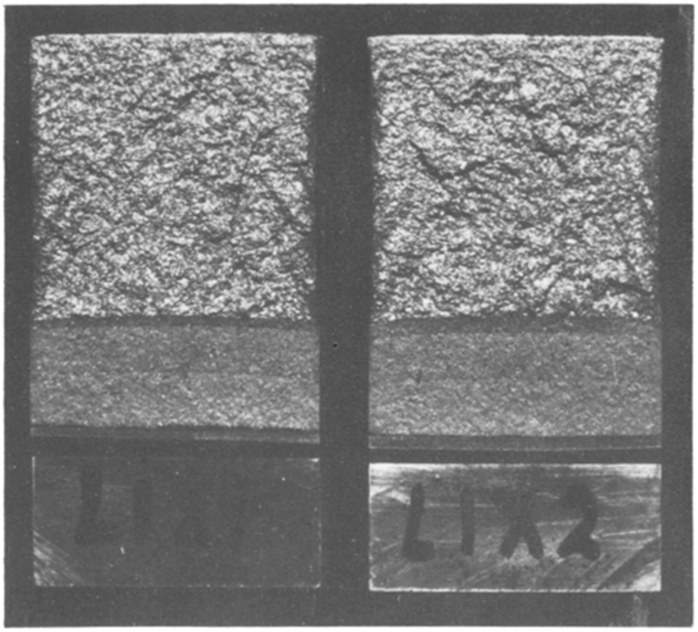

Figure 8 Fracture surfaces of 25 mm thick specimens of steel L.

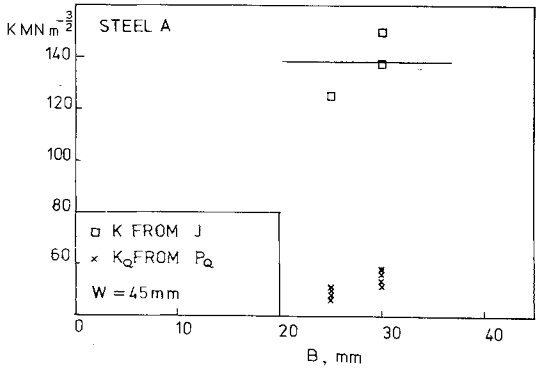

Figure 9 K_{IC} values estimated from J at fracture initiation and K_Q values corresponding to sudden yielding in steel A.

toughnesses correspond to prominantly cleavage fractures as shown in Fig. 10. Again the fractures are of a plane strain character as judged by the small shear lips.

Crack tip COD varied from 0.18 to 0.29 mm and gave a stress intensification factor, n, of 0.9 ± 0.2, assuming a K_{IC} of 138 MN m$^{-3/2}$.

4. Discussion of results

At the outset of this testing programme it was decided to use LFM, COD and J-integral methods since it was envisaged that the lower strength steels would not behave in a linear elastic manner, and that using all methods conjointly on the higher strength steels which could be assessed by LEFM methods would give confidence in toughness assessment of the lower strength steels by general yielding fracture mechanics. This, in fact, proved to be the case, the confidence in the general yield fracture mechanics arising from the results presented in paper I. A confusing aspect of the low strength steel results was the sudden yield phenomenon which gave the appearance of LFM behaviour. Such behaviour has been confirmed by other workers on this steel [9].

The estimates of K_{IC} for the steels described here are 67 MN m$^{-3/2}$ for D, 86 MN m$^{-3/2}$ for L and 138 MN m$^{-3/2}$ for steel A. These are relatively tough materials and critical defect sizes derived from these figures would indicate defect tolerances much greater than appreciated by current codes of practice for pressure containing parts, for instance.

It is somewhat surprising that the COD results tend to show stress intensification factors of about 1 even when the fracture surfaces indicate predominantly plane strain fracture. However, there do appear to be other instances of this type [10].

Acknowledgements

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Figure 10 Fracture surfaces of 25 mm thick specimens of steel A.

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