AN INTER-LABORATORY PROGRAMME OF DYNAMIC FRACTURE TOUGHNESS TESTS

This paper has been written by the I.I.W. (Commission X) U.K. Briefing Group on dynamic fracture toughness testing which comprises:

P.R. Christopher[1], (Chairman), C.L. Formby,[2] (Secretary), D.F. Cannon[3], C.H. Jones[4], M.S. Kamath[5], G.M. Lees[6], D.T.W. McNicol[7], D. Milne[6], A.H, Priest[8], M.W. Shanahan[9], C.E. Turner[10] and P.A.J. van der Veer[11].

1. Admiralty Marine Technology Estab. (EDU), Portsmouth. 2. Central Electricity Generating Board, N.W.R. Scientific Services Dept., Timpson Road, Manchester, M23 9LL. 3. British Railways Board, Research and Development Division, Derby. 4. Military Vehicles Engineering Estab., Christchurch. 5. Welding Institute, Cambridge. 6. British Gas Corporation, Engineering Research Station, Newcastle upon Tyne. 7. Admiralty Marine Technology Estab. (S), Dunfermline. 8. British Steel Corporation, Sheffield Laboratories, Rotherham. 9. Research Laboratory Services Division, Health and Safety Executive, Sheffield. 10. Imperial College, London. 11. Koninklijke Shell Laboratory, Amsterdam.

ABSTRACT

The Working Group, which has the task of developing a practical technique of dynamic fracture toughness testing suitable for inclusion in British Standards, has previously made some detailed proposals (Christopher and co-workers, 1976). Following this, the Group decided to verify the applicability of the test specifications by carrying out a series of tests on a single steel (BS11 rail steel).

Eleven laboratories participated and tests were carried out in accordance with the specifications proposed. Initially, tests were carried out at room temperature and three strainrates. Further series of tests were then done at a single strainrate and three temperatures. These conditions were chosen so as to encompass both LEFM and PYFM behaviour.

The results are presented and an acceptable level of reproducibility is found. A statistical study is described, relating the variability to a number of equipment and test characterising parameters. Variation between laboratories is shown to be less than the specimen to specimen scatter. The latter is not correlated with any principal single cause, which is taken to indicate that the test procedure is sound. However, some small changes are proposed in the test specifications.

KEYWORDS

Fracture; stress intensity factor; dynamic loading; British Standards; K_{IC}; crack propagation; rail steel.

INTRODUCTION

Dynamic fracture toughness measurements are relevant in the practical application of fracture mechanics to engineering components under two circumstances. Firstly, in assessing the integrity of structures which contain crack-like planar defects and are subject to suddenly applied loads. Examples in this category include railway rails, land or marine vehicles and so on. Secondly, in statically loaded structures rapid loading may result from some malfunction which must be catered for in the design (e.g. pressure vessels in engineering transient loading situations). In these situations, the loading rates involved will exceed significantly the "static" rate, i.e. rate of rise of stress intensity factor, $\dot{K}$, of 2.5 MPa $m^{\frac{1}{2}} s^{-1}$, at which conventional fracture toughness (K_{IC}, COD) measurements are conducted using well established procedures (BS 5447, 1977; BS 5762, 1979). A major drawback in the dynamic initiation case is the absence of any standard test procedure to determine fracture toughness.

An attempt was made by members of this working group (Christopher and co-workers, 1976) to resolve the difficulty by putting forward draft proposals which would be compatible with the slow rate procedures. It was recognised that as a result of the high loading rates used and the associated problems of inertial loads, response of load and displacement transducers, electronic noise and pick-up; high speed data acquisition, etc., which are unique to such tests, special provisions would have to be incorporated into the new proposals. Ireland (1976) has dealt with some of these aspects in relation to impact testing. The Working Group was also interested in examining related aspects, such as validity criteria, linearity requirements, and if the clip gauge could be dispensed with in dynamic testing.

The present programme of collaborative tests was therefore initiated to test the Working Group draft proposals. The objectives of the study, in addition to the validation exercise were:-

a) To examine any limitations of high rate servo-hydraulic systems and allied instrumentation.

b) To provide an opportunity for a number of interested laboratories to familiarise themselves with high rate testing, and

c) To assess the extent of inter and intra-laboratory scatter likely in dynamic fracture toughness measurements.

This paper presents a brief summary of the extensive programme of tests undertaken by the participating laboratories and discusses their implications in drafting a standard. In passing, it may be noted that a similar round-robin programme of tests has also been in progress in the USA under the aegis of an ASTM Task Group (E24.01.06).

EXPERIMENTAL DETAILS

Eleven laboratories participated in various stages of the collaborative programme and these are listed as the authors' affiliations on the title page. They have been given the code letters A,B,C,D,E,F,G,H,I,J and K, but not in the same order as the title page.

Material

The material used was a 18m length of rail steel produced by the acid-Bessemer process to the requirements of BS.11 (Flat Bottom Railway Rails, 1959). The specified and actual compositions of this ferritic/pearlite steel are given in Table 1. The rail was in the as-rolled condition. This type of steel is in general use in the UK. European, American and Japanese standard rail steels are very similar.

TABLE 1 - Rail Steel Composition

	Carbon (%)	Silicon (%)	Manganese (%)	Sulphur (%)	Phosphorus (%)
BS.11 Specification (Acid Bessemer)	0.4-0.5	0.05-0.35	0.95-1.25	0.06 (max)	0.06 (max)
Cast No. 3844 (used in this study)	0.44	0.1	1.08	0.034	0.035

Rail steel was chosen for the programme because the data from the tests would be relevant to a practical problem (Cannon and Sharpe, 1978).

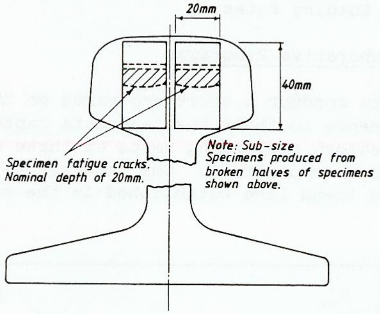

Fig. 1. Specimen location in rail section.

Specimens

Single edge notched, three point bend specimens were machined from the rail head as shown in **Fig. 1**. Specimens were initially produced 20 mm thick (B) by 40 mm deep (W) with all other dimensions in accordance with the requirements of BS 5447 (1977). Smaller specimens were later machined from the broken halves of some of these specimens. Some of the small specimens had B and W equal to 20 mm; (type I), others were 10 mm thick and 20 mm deep (type II); the fatigue cracks had the same orientation as in the larger specimens.

140 specimens were produced for the main collaborative programme, and these were randomly distributed amongst the laboratories participating.

Machines and Instrumentation

All of the laboratories used servo-hydraulic machines of the type commonly used for fracture and fatigue tests. Tests were performed with displacement control.

Conventional load cells and clip gauges were used with the exception of Laboratory B which used a ring type clip gauge.

Methods used for recording data included analog tape recorders using record tape speeds of 60 inches per second or digital storage transient recorders. Visualisation of the analog tape data was either by ultra violet (U.V) oscillograph, C.R.O., or analog X-Y, time recorders. In the latter case the original analog tape data were transferred to a digitial transient recorder to increase data transfer time to the analog X-Y recorder. Data were not conditioned by deliberate filtering.

Graphs of load against time, cross-head displacement against time and clip gauge displacement against time were thereby obtained. The data were also used to produce a cross-plot of load against clip gauge displacement.

Exploratory Programme

Prior to the start of the main programme, laboratory F conducted an exploratory study to determine the fracture behaviour of the rail steel at +23°C and +65°C between $\dot{K}$ rates of 10^{-1} and 6 x 10^{4} MPa $m^{\frac{1}{2}}$ s^{-1}. These results suggested that at room temperature the fracture toughness was slightly dependent on loading rate and virtually elastic, whilst at +65°C fracture behaviour was elastic-plastic particularly at low loading rates.

Phase 1 of the Collaborative Programme

The first task was to conduct a short programme so that each laboratory could build up some confidence in their test and data capture technique. This programme comprised each laboratory performing tests at three nominal K's of 10^{0}, 10^{2} and 10^{4} MPa $m^{\frac{1}{2}}$ s^{-1} at room temperature. The results of these tests are shown in Fig. 2 together with the trend line established in the exploratory programme.

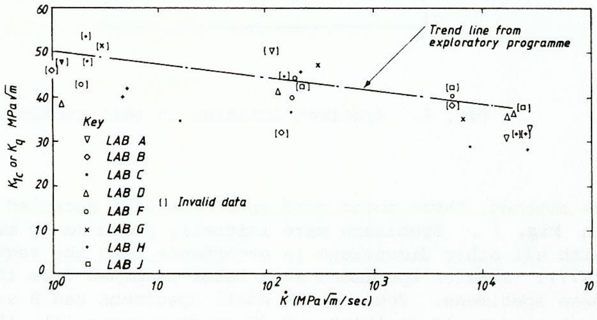

Fig. 2. Results of Phase 1, tested at room temperature

Whilst these results were encouraging, it was clear that most of them were just beyond the limits of L.E.F.M. validity criteria as, for example, specified in BS 5447, although deformation and hence crack opening displacements at fracture were very small. These features contributed to analysis problems since, in this border-line area, the analysis of data, even in quasi-static tests, was prone to subjective judgement (e.g. drawing tangents to load v. crack mouth opening records) and consequently the spread of data was large. Since the objective of this programme was concerned with the validation of high loading rate test techniques, it was decided to proceed with testing at two temperature levels, above and below ambient, which would place results firmly in the L.E.F.M. or yielding regime.

Phase 2

After some further exploratory testing it was found that during fracture at -20°C conditions were near to plane strain and +100°C produced general yielding and tearing prior to attainment of maximum load. These were therefore the temperatures chosen for Phase 2.

An intermediate loading rate, 10^{3} MPa $m^{\frac{1}{2}}$ s^{-1}, was decided upon so as to be attained readily by all of the laboratories involved, and avoid any complications from inertial effects.

Three laboratories (A,C and F) did the testing at -20°C and each tested six standard specimens. In addition, laboratory C tested subsize specimens of both types I and II. Laboratory F tested type I subsize specimens.

Three further laboratories (B,G & I) did the testing at +100°C, again testing six specimens each.

Finally, seven laboratories assessed independently the same set of data - the fifteen results at 100°C. This was to expose the amount of subjectivity which is inherent in measuring up a particular graph.

RESULTS - ANALYSIS AND DISCUSSION

Reproducibility

Taking just the twelve fully valid tests at -20°C on standard specimens, the mean value measured was 30.6 MPa $m^{\frac{1}{2}}$ with a standard deviation of 2.1 MPa $m^{\frac{1}{2}}$. This is, in the context of fracture results generally, a quite acceptable standard of performance and suggests the test specifications are adequate.

Some tests at -20°C were invalid and it is interesting to include the results of these, when it is found that the mean value becomes 30.1 MPa $m^{\frac{1}{2}}$ and the standard deviation 2.6 MPa $m^{\frac{1}{2}}$, out of sixteen tests. The slight increase in standard deviation when invalid results are included does exemplify the advantage of following the Standard, but this point is examined further below in relation to the effect of changes in various test parameters.

The sub-size specimens of type I were different only in that W and a were reduced and so the size reduction should not affect K_{IC}. This turned out to be the case. Including these in the mean gives 30.3 MPa $m^{\frac{1}{2}}$ with standard deviation 2.4 MPa $m^{\frac{1}{2}}$, from a total of twenty-five values.

For standard-sized specimens at 100°C where, because of the much higher ductility, the crack opening displacement (δ_c) at maximum load has been taken as the measure of toughness, the mean value of the fifteen results was 0.065 mm with a standard deviation of 0.036 mm. (For the present purpose, δ_c, is calculated from ram displacement at time of fracture - see below). It is the view of the Working Group that this rather poor reproducibility of 100°C tests is more the result of being within the upper part of the transition range of the steel than an intrinsic shortcoming of the test procedure.

Analysis

In the case of results at -20°C, a statistical technique, analysis of variance, was used to determine whether there was a significant difference between laboratories. A related technique, multiple regression analysis, was used to assess the correlation between K_{IC} and K_f, $\dot{K}$, B, $^{a}/W$, presence of pop-in (P = 0 or 1), a_{mean}, a_{max}, a_{min},

a_{25}, a_{50} and a_{75}. (K_F is stress intensity factor applied in fatigue precracking and a is crack length. Subscripts 25, 50 and 75 refer to position of measurement as a percentage of B.)

(1) Difference between laboratories

It is clear in **Fig. 3** that there is little effect of testing laboratory. Analysis of variance showed that there was no significant difference between laboratories at the 95% confidence level. It was found that almost all (99%) of the error was due to sampling and this was further broken down as follows.

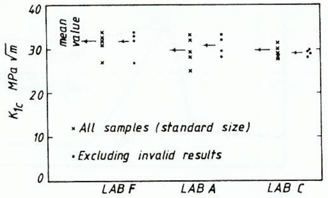

Fig. 3. Results of testing standard sized samples at -20°C.

(2) Effect of K_F

Fatigue precracking was carried out at K levels below $0.7K_{IC}$ and when K_{IC} was plotted against K_F no systematic effect of K_F was found. When multiple regression analysis was carried out to detect correlations between K_{IC} and various parameters, a very weak dependence of K_{IC} on K_F was apparent (see Table 2).

TABLE 2

Parameter	Value of coefficients (for K_{IC} in MPa $m^{\frac{1}{2}}$, lengths in mm)	
	A	35.48
a_{50}	B	7.39
a_{max}	C	-7.28
B	D	0.285
P	E	-2.707
K_F	F	-0.46

Results of multiple regression analysis giving apparent correlations between K_{IC} and the parameters : K_F, $\dot{K}$, B, $^W/a$, P, a_{mean}, a_{max}, a_{min}, a_{25}, a_{50} and a_{75}.

The following linear equation was found to incorporate 76% of the variation in K_{IC}:-

$$K_{IC} = A + Ba_{50} + Ca_{max} + D\,B + E\,P + F\,K_f$$

The order of significance was:-

a_{50}, a_{max}, B, P and K_F

(3) $\dot{K}$

The multiple regression analysis of the Phase 2 tests at -20°C did not indicate K to be a significant parameter. This was in accord with expectations, as the Phase 1 tests had already shown K_{IC} to be weakly dependent on $\dot{K}$ even when this parameter was varied deliberately over a wide range (Fig. 2).

(4) B

Table 2 shows the effect of thickness to be well down the order of significance. Any variations observed could be attributed to inherent variability of an as-rolled section.

(5) $^a/W$

It came out of the analysis that $^a/W$ is not an important variable. However, in weighing this finding it should be borne in mind that $^a/W$ did not vary considerably between tests.

(6) P

Whether or not pop-in was detected did not affect K_{IC} greatly as can be seen in Table 2. The small effect apparent is in the expected direction, in that the occurrence of a fracture load measured at pop-in correlated with slightly lower K_{IC} values.

A correlation was found between pop-in and crack front straightness (see below).

(7) a_{mean}, a_{max}, a_{min}, a_{25}, a_{50}, and a_{75}

These parameters describe the crack length at various positions along the crack front and combinations of them describe the profile of the crack. The fact that the regression analysis includes invalid tests means that an appreciable variation of crack front obliquity or curvature is present since this was found to be the main cause of invalidity. A considerable variation of crack length is also incorporated since sub-size specimens are included.

At first sight it appears that crack length is affecting the results since a_{50} and a_{max} are first in order of significance in Table 2. However, this is seen to be an effect rather of $(a_{max}-a_{50})$ since B = -C. The parameter $(a_{max}-a_{50})$ quantifies in fact the obliquity of the crack, and would be zero for a straight or symmetrically bowed crack front. This dependence on crack profile is not unexpected and underlines the importance of the strict limitations in the Testing Standard in this respect, contrary to a current tendency of opinion to advocate some relaxation.

Correlation of Pop-in with Crack Straightness

Further indication of the importance of crack front profile in determining the behaviour is seen when any departure from the BS.5447 (1977) requirements for crack straightness, which are also those proposed by this Working Group (Christopher and co-workers, 1976), are correlated with the occurrence of pop-in. In Table 3, Class 1 denotes tests conforming to the Standard, Class 2 those outside the Standard. All tests from Phases 1 and 2 are included, with the exception of some in which the detection of pop-in was suspect. Using a difference in proportions test, it was found that there was a significant difference between Class 1 and Class 2 for the incidence of samples showing pop-in. This test was carried out at the 95% confidence level.

TABLE 3. Correlation between Pop-in and Crack Straightness

Class	Total No. of Tests	Tests with pop-in	Tests without pop-in
1	30	20	10
2	11	2	9
	41	22	19

It is concluded that improving crack straightness increases the likelihood of pop-in, but has less effect on K_{IC} (compare valid and invalid means and S.d's in the section on Reproducibility. This is consistent with the comparatively weak effect of P on K_{IC} (see order of significance in Table 2).

Requirement for Linearity of Elastic Line

The programme of collaborative testing has shown that in the earlier proposed Standard (Christopher and co-workers, 1976) the "elastic" portion of the traces was required to be linear within unrealistically tight limits. Perusal of all the traces by the Working Group led to the consensus that it would be sufficient to require that the upper 50% only be linear and not 66%. This is also in accord with present opinion within the American E24 Committee.

Similarly, the limit of 2.5% variation in gradient was considered unrealistic. A modified secant offset procedure has been proposed by the E24 Committee for use in analysing dynamic clip gauge records. The procedure enables less than perfectly linear records to be used if the top 50% of the record up to K_Q lies within an envelope $\pm$ 5% of P_Q on either side of a mean straight line drawn through the load-clip gauge record, where K_Q and P_Q are provisional values of stress intensity and load. This procedure has been applied to the present analysis with further modifications. The envelope was drawn in such a way as to optimise the amount of the record within it and the procedure was extended to the analysis of load-time records. However, we consider that further experience is necessary before this method becomes fully proven.

Instrumentation

The general data acquisition requirement was that each laboratory should provide records of force versus time, force versus clip gauge displacement (direct or as cross-plots of two time base signals) and ram displacement versus time. The latter was required principally to assess the actual displacement rate during the tests. In recording such data at high rates of testing problems may arise from three general sources.

Firstly, the presence of inertial loads on the elastic portion of force-time records can lead to erroneous estimates of the fracture toughness, as discussed in the context of instrumented impact testing by Ireland (1976). However the magnitude of the inertial force is greatly dependent on the impact velocity and since $\dot{K}$'s were generally less than 10^4 MPa $m^{\frac{1}{2}}$ s^{-1} in the present series of tests, inertial effects did not pose serious problems in interpretation of test traces.

Secondly, and this related directly to instrumentation design, all components of the data acquisition and recording system should have adequate response at the testing rate. This includes both the mechanical response (governed by the natural or resonant frequency) of transducers as well as electronic response of signal conditioning and recording equipment. A systematic investigation of the response times of the equipment used by various laboratories was not conducted since response was not generally a major problem within the range of $\dot{K}$'s examined.

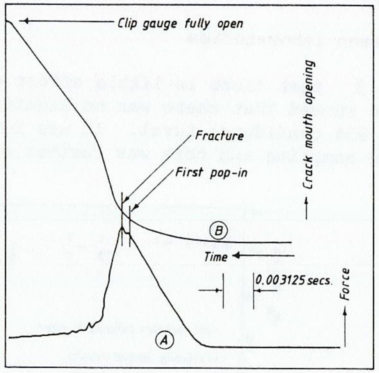

Fig. 4. Load cell and clip gauge responses.

Figure 4 shows load cell and clip gauge outputs versus time where response was borderline for a -20°C test at a $\dot{K}$ of 4.5 x 10^2 MPa $m^{\frac{1}{2}}$ s^{-1}. It is seen that the fall-off in load after fracture is not instantaneous so that slopes of the record prior to and after fracture are not vastly different. This is indicative of lack of response in the load cell as the time to fracture i.e. rise time of the force signal, is short enough to drive the load cell into resonance. At $\dot{K}$'s well above 10^4 MPa $m^{\frac{1}{2}}$ s^{-1}, conventional load cells were often found to be inadequate. It appears, therefore, that special low mass transducers of enhanced stiffness are needed. Alternatively, strain gauge load cells should be replaced by high response piezoelectric quartz load washers for these levels of $\dot{K}$. Typical figures of resonant frequencies for load cells in the present study varied from 250Hz to 1000Hz. Clip gauge response was dependent on the length of the beams. Thus, by using short-legged clip gauges, the resonant frequency can be enhanced.

The third major instrumentation problem encountered was that of noise on signals, which appeared to be more pronounced on clip gauge output. This affected the identification of pop-ins, which, as per existing quasi-static testing standards, is facilitated by cross-plotting force and crack mouth opening displacement. Although most laboratories succeeded in reducing noise to an 'acceptable' level on each individual transducer, the combined noise on transducer cross plots was clearly a problem. Fig. 5 shows an illustration where the individual noise levels are low but the cross plot noise is considerably worse; in this case, the pop-in has been just about lost. The effect of introducing a 1000Hz real time smoothing filter is to almost eliminate pop-in from the record. There is clearly scope for further development of low-noise transducers and data recorders to improve the signal to noise ratio.

Estimation of COD without the Use of a Clip Gauge

In conventional or quasi-static fracture testing, the use of a crack mouth opening displacement gauge has been standardised since it serves a number of purposes. (a) it is believed to be more responsive to detecting the incidence of pop-ins, (b) it provides the basis for the 5% offset secant procedure for identifying excessive non-linearity in the elastic analysis, (c) in cases where the specimen fails to behave in a valid l.e.f.m. manner, the displacement gauge provides an alternative measure of fracture toughness, namely, crack opening displacement (COD).

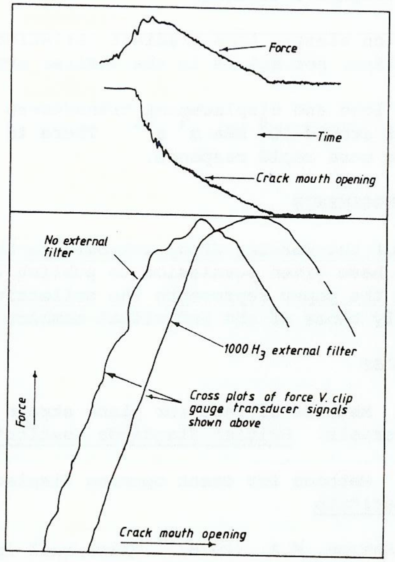

Fig. 5. Noise on transducer signals

Similar criteria apply for using clip gauges in dynamic testing and a clip gauge is mandatory in our earlier proposals (Christopher and co-workers, 1976). However the requirement is overshadowed by practical difficulties in using the gauge. Most significantly, at very high rates, say K's above 10^4-10^5 MPa $m^{\frac{1}{2}}$ s^{-1}, clip gauges do not accelerate rapidly enough to follow the changes in crack mouth opening. Of course, in the rates utilised in this study, gauge response was not a major issue. A further problem with displacement gauges appears to be their greater susceptibility to picking up noise and interference, as indeed observed in this study. (Fig. 5). This undermined the use of the clip gauge for purpose (a) above. It was found that a clean load-time trace was best for the detection of pop-in.

In view of the above the Working Group decided to examine the possibility that the clip gauge could be dispensed with at high rates and use an alternative estimation procedure for COD. Provision to estimate COD under these circumstances had earlier been included in the original draft proposals (Christopher and co-workers, 1976). The method of COD determination took account of the geometrical relationship between specimen load point displacement and COD, the load point displacement being derived from the ram displacement rate, $\dot{\Delta}$ and the time taken during plastic deformation, t_p, obtained from the load/time trace. (Fig. 6). The relationship for calculating COD is:

$$\delta = \frac{K^2 (1-\nu^2)}{2\sigma_y E} + \frac{0.4(W-a)}{W}\dot{\Delta}\, t_p$$

Where ν is Poisson's ratio, E is Young's modulus and σ_y is yield stress. It should be noted that this equation is only valid where material properties in the crack region are homogeneous. The origins of the expression may also be traced to the current COD standard (BS 5762, 1979).

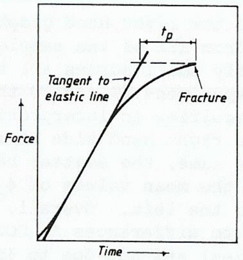

Fig. 6. Schematic force/time curve

A comparison was made between the COD values calculated by the two techniques at various loads for the 100°C test results of laboratory G. In order to allow this comparison to be made at high values of COD as well, test results from 1.5% manganese steel and Type 316 stainless steel specimens, tested in a quasi-static manner, were also analysed. The results showed a good relationship between the two methods (Fig. 7) although the COD values determined from the load/time traces were consistently lower than those obtained from the load/clip gauge. This indicates that estimated values of COD can be used conservatively in design.

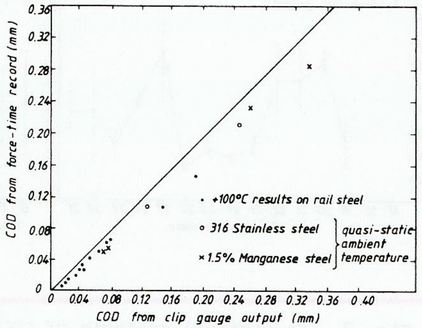

Fig. 7. Comparison of two different methods of measuring COD.

In view of the encouraging trends provided by the approximate estimation procedure, and the fact that the force-time records picked up pop-ins with sufficient reliability it is felt that the use of clip gauges in such tests may not be necessary after all. However, in the absence of a clip gauge it becomes important to carry out the test in such a way that $\dot{\Delta}$ is known and constant.

Inherent Subjectivity in Inter-Laboratory Analysis of +100°C Results

Since the COD estimation procedure involves a measure of subjectivity in that a special construction is necessary to obtain t_p, it was felt that there was greater scope for inter-laboratory differences in the estimated COD values. To assess the seriousness of this potential source of error, test records from the +100°C tests (15 in all) were sent to all the laboratories for independent analysis. Seven laboratories responded and the resulting data from the two procedures, load versus clip gauge and load versus time, was analysed statistically. Figure 8 shows typical variations of the means and standard deviations observed in this data. The left hand side presents the mean and SD of each of the samples calculated from all laboratory results, while the right hand graph shows mean and SD for each of the laboratories calculated from all of the sample results. On the left hand side, the scatter is consistently small across all the laboratories for most specimens. In a few cases, notably specimens 29 and 30 the scatter band is very wide and therefore points to difficulties in interpreting the test record, possibly a result of a bad trace. From the right hand side it is seen that the scatter within each laboratory is roughly the same, the scatter band itself being fairly wide. Furthermore, in general, the mean values of δ_c on the right show distinctly less variations as compared to the left. Overall, these trends combine to show that the primary contribution to differences in COD arises from the material itself (i.e. scatter in properties) and not due to inter-laboratory differences in analysis.

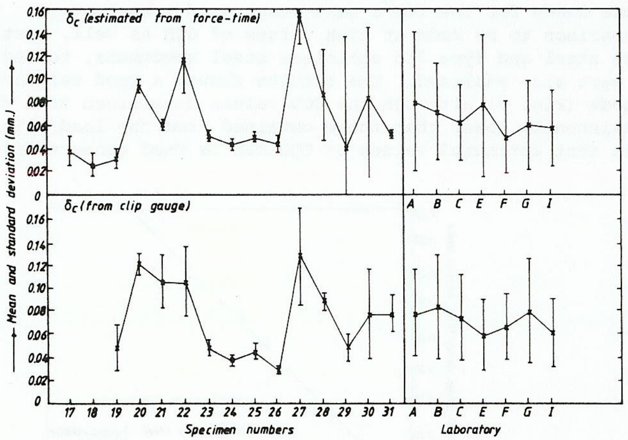

Fig. 8. Statistical analysis of COD values.

CONCLUSIONS

1. The experimental scatter between L.E.F.M. valid tests at -20°C was acceptably small. No specific source of scatter could be identified and no systematic difference between laboratories was detected by analysis of variance. It is concluded that the proposed Standard (Christopher and co-workers, 1976) is sufficiently restrictive.

2. When invalid -20°C tests were included the experimental scatter increased slightly. The source of scatter most clearly identified by multiple regression analysis was deviation from the crack front straightness requirement. It is concluded that this requirement must not be relaxed in any future proposed Standard.

3. Crack straightness was found to influence the incidence of pop-in.

4. Statistical analysis of the +100°C data indicates that the variations result primarily from material property scatter. Inter-laboratory differences are only a secondary factor.

5. The use of a clip gauge should not be made mandatory in a Standard for dynamic fracture toughness testing.

6. Restrictions on elastic line gradient variation should be applied only to the upper 50% of the line, not 66% as in the earlier proposals.

7. Conventional load and displacement transducers are approaching their limiting response at $\dot{K}$'s of around 10^4 MPa $m^{\frac{1}{2}}$ s^{-1}. There is scope for the development of transducers with a more rapid response.

ACKNOWLEDGEMENTS

The members of the Working Group acknowledge the generous support of their organisations who have given permission to publish this paper. However they wish to point out that the paper represents the collective views of the Working Group and not necessarily those of the individual members and their organisations.

REFERENCES

B.S. 5447 (1977). Methods of test for plane strain fracture toughness (K_{IC}) of metallic materials. British Standards Institute.

B.S. 5762 (1979). Methods for crack opening displacement (COD) testing. British Standards Institute

Cannon, D.G. and Sharpe, K.A. (1978). Wheel/rail impact loads - a contributory cause of rail fracture. International Conf. on Analytical and Experimental Fracture Mechanics. Rome.

Christopher, P.R. and co-workers (named on title page of this paper) (1976). Some proposals for dynamic toughness measurements. Proc. of International Conf. on Dynamic Fracture Toughness. Welding Institute. pp 127-145.

Ireland, D.R. (1976). Critical review of instrumented impact testing. Proc. of International conf. on Dynamic Fracture Toughness. Welding Institute. pp.47-62.

Seeley, R.R. (1976). Recommended procedure for characterising the frequency response of load and displacement measuring circuits., Note to ASTM E24.01.06 Task Group on Dynamic Initiation.