Dynamic Fracture Properties of Steel A533 B Cl.1 Evaluated from Experiments on Large Compact Crack Arrest Specimens

B. BRICKSTAD, L. DAHLBERG
The Swedish Plant Inspectorate, Stockholm, Sweden
A. LUNDBERG
The Norwegian Institute of Technology, Trondheim, Norway
K. RAHKA
Technical Research Centre of Finland, Espoo, Finland
C. DEBEL
Riso National Laboratory, Roskilde, Denmark

ABSTRACT

In a joint Nordic project the dynamic fracture properties of steel A533 B Cl.1 have been determined with the use of large compact crack arrest (CCA) specimens, 400x400x100 mm in size. A total of eight experiments were conducted, four in Norway, two in Finland and two in Denmark. The results of the experiments showed that the CCA-specimen has a suitable geometry for determination of dynamic fracture properties. The method of strain gauges was used as the basic method for measurement of crack length as function of time. The method gave distinct strain peaks which could be analysed by FEM for evaluation of the time instant of crack tip passage. The evaluation of the experiments resulted in crack propagation toughness values which, as can be expected, show an increase with increasing crack velocity. The obtained crack arrest toughness values agree well with values reported in the literature.

1 INTRODUCTION

The theory for analysis of rapid crack propagation and arrest is now well developed, at least for materials which mainly show linear elastic behaviour. In general finite element methods (FEM) including dynamic effects have to be used for proper analysis. To enable analysis of rapid crack propagation and design for crack arrest, the dynamic fracture properties of the material have to be known. The primary aim of a joint Nordic project with participants from Denmark, Finland, Norway and Sweden has been to develop experimental techniques for determination of dynamic fracture properties and to generate data for steel A533 B Cl.1. The conclusions from the studies of experimental technique were presented at SMIRT 10 (Brickstad and Dahlberg 1989), while this paper will concentrate on the experimental dynamic fracture toughness results of the project. A more detailed report of the project results is given by Dahlberg (1989).

2 LARGE COMPACT CRACK ARREST (CCA) SPECIMENS

A series of eight instrumented crack arrest experiments with the CCA-specimen was conducted, four at the Norwegian Institute of Technology (SINTEF), two at The Technical Research Centre of Finland (VTT) and two at Risø National Laboratory in Denmark. The size of each specimen was approximately 400x400x100 mm.

The material used was A533 B Cl.1 steel with RT_{NDT} = -23°C. It was supplied from the HSST-program at Oak Ridge National Laboratory (ORNL), USA, which performed six wide-plate tests in 1985-86. The CCA-specimens were cut from the fractured wide-plates. The orientation of the CCA-specimen cracks was chosen the same as the orientation of the cracks in the original wide-plates, i.e. perpendicular to the rolling direction.

The type of specimen used is a weld-embrittled side-wedge-loaded CT-specimen according to the ASTM-standard E 1221 (1990). The geometry and the processing of the embrittled weld are in accordance with the standard.

3 QUASI-STATIC ANALYSES

The following table specifies some geometrical dimensions and recorded values of the four tests which could be evaluated.

	T	a_o	a_f	δ	B	B_N	ASTM K_{Ia}
SINTEF-1	-18°	118	274	δ_A=2.00	98	82	86.1
SINTEF-2	-16°	118	270	δ_A=1.80	98	82	77.5
VTT-2	-15°	120	276	δ_B=1.09	100	80	94.0
RISØ-1	-16°	107	178	δ_D=1.15	99.5	80	89.6

T = test temperature, °C
a_o = initial crack lenth, mm
a_f = arrested crack length, mm
δ_A, δ_B, δ_D = measured crack opening displacement (mm) at position A, B and D at initiation of crack growth, see Fig. 1
B, B_N = unnotched and notched thickness of specimen, mm
K_{Ia} = crack arrest toughness (MPa√m) according to the ASTM-standard E 1221 (1990).

The quasi-static K_{Ia}-values from our tests agree well with values reported from ORNL (Nanstad 1987)

4 DYNAMIC ANALYSES

Strain gauges were used to measure the crack length as function of time. Four to six strain gauges were used on each specimen, see Fig. 1.

As the advancing crack passes a strain gauge, a peak occurs in the strain-time response of the gauge. Knowing the strain gauge locations and the time at which the strain peaks occur, the average crack velocity between the reference points can be estimated.

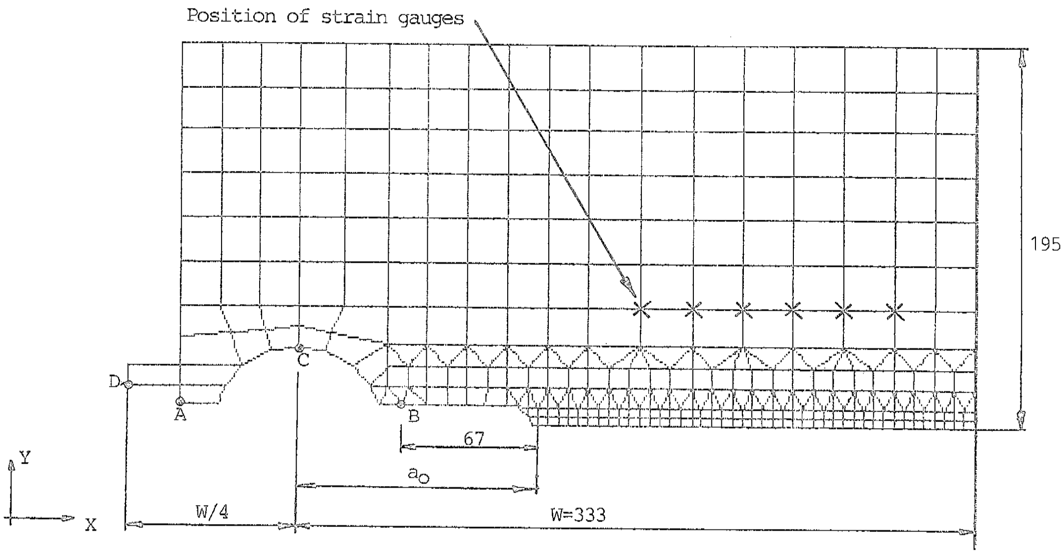

Fig. 1. Finite element mesh of upper half of CCA-specimen.

Fig. 1 shows the finite element mesh used for analysis of the experiments. The crack growth model adopted is the well established gradual node relaxation technique (Rydholm et al. 1978). All experiments were analysed assuming linear elastic behaviour. To obtain some idea of the role of non-elastic effects, one evaluation was also performed using Perzynas viscoplastic material model (Perzyna 1966).

Due to difficulties with the signals from the strain gauges only three experiments were judged to give reliable enough data to enable a complete dynamic analysis. The SINTEF-2 experiment is here chosen for closer presentation. In this experiment a set of six gauges were placed 58 mm above the intended crack plane. The spacing between the gauges were approximately 25 mm and the first gauge was located 55 mm from the initial crack-tip. Fig. 2 shows the recorded strain signals ε_y-ε_x as function of time for the second gauge.

The propagating crack-tip creates a singular strain field which can be traced by the strain gauges. By performing numerical finite element evaluations with different crack growth histories the computed strains can be matched against the experimental results. The numerically evaluated strain signals are also shown in Fig. 2 for the crack velocity that was considered to be the best estimate. Both the location and the width of the singular strain peak can be used to evaluate the crack velocity. It is seen that the peak of the strain signal is generally recorded some time before the actual passage of the crack tip. This is also what is theoretically expected. As shown by Fig. 2, at least the location of the numerically evaluated strain peaks seems to agree reasonably well with the experimental value.

The experiments appear to give a quite high strain level also after the passage of the crack-tip. This behaviour was not reflected in the numerical evaluations, not even by including rate-dependent plasticity as shown by Fig. 2. One explanation might be that the gauges are permanently strained by the strain peak.

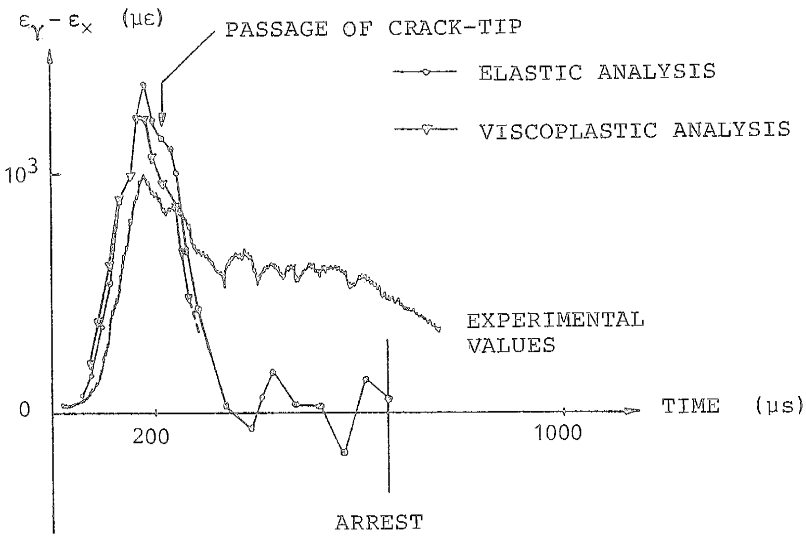

Fig. 2 Strain $\varepsilon_Y - \varepsilon_X$ as function of time for the second strain gauge. Experimental and numerical evaluations.

By using the so evaluated crack growth histories, the dynamic stress intensity factor K_I^d as function of time was calculated. The result is shown in Fig. 3 for the SINTEF-2 experiment. Also shown in the figure are the measured crack-tip position a(t) from the strain gauge signals and the corresponding quasi-static stress intensity factor K_I^s.

It is observed that the dynamic effects on K_I seem to be fairly small, at least for the latter part of the propagation event. At crack arrest the difference between K_I^s and K_I^d is less than 10 percent in all three experiments.

The following table compares the dynamically evaluated K_{Ia} with the quasi-static K_{Ia} from the ASTM-standard E 1221 (1990).

Experiment	K_{Ia} (dyn) $MPa\sqrt{m}$	K_{Ia} (static) $MPa\sqrt{m}$
SINTEF-1	94.1	86.1
SINTEF-2	82.8	77.5
VTT-2	96.3	94.0

It is observed in this case that taking dynamic effects into account results in slightly higher crack arrest toughness values.

For the SINTEF-2 experiment a viscoplastic evaluation was also made. The resulting pseudo stress intensity factor is shown in Fig. 3. As expected, the introduction of viscoplasticity results in considerably lower values. A direct comparison with the elastodynamic K_I is not meaningful. However, it is interesting to note the size of the active plastic zone ahead of the propagating crack tip, which varied from initially 15 mm to 2.5 mm prior to crack arrest for this experiment. Apparently, the plastic yielding was quite small when the crack arrested.

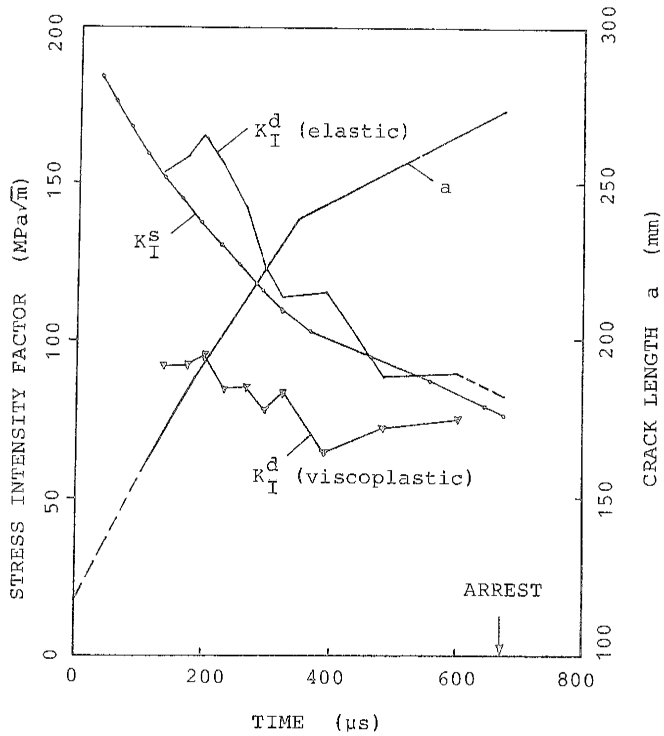

Fig. 3. K_I^s, K_I^d and crack length as functions of time for experiment SINTEF-2.

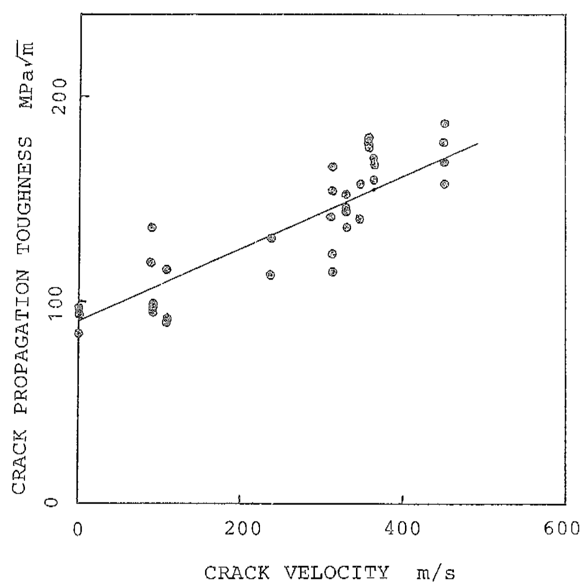

Fig. 4. Crack propagation toughness K_{pc} as function of crack velocity for A533 B Cl.1 with $T - RT_{NDT}$ = 5 to 8° C.

From the evaluations, the crack propagation toughness K_{pc} as function of crack velocity can be deduced. The result is shown in Fig. 4 and the expected upward trend can be seen. Some portion of the observed scatter is probably due to the uncertainties in the experimental measurements.

6. CONCLUSIONS

1. The surface method for estimation of crack velocity based on strain gauges seems to work well on large CCA-specimens if no crack tunneling effects occur.

2. Dynamic effects on the stress-intensity factor seem to be relatively small during a crack arrest test with the CCA-specimen.

3. The found crack propagation toughness values show an upward trend with increasing crack velocity as can be expected. The crack arrest toughness values agree well with the values reported by ORNL (Nanstad 1987).

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