EXPERIMENTAL DETERMINATION OF DYNAMIC FRACTURE TOUGHNESS BY J INTEGRAL METHOD

B. Marandet, G. Phelippeau, G. Sanz

Institut de Recherches de la Sidérurgie Française (IRSID)
185, Rue du Président Roosevelt 78105 Saint Germain-en-Laye (France)

ABSTRACT

Fracture toughness tests are conducted on fatigue precracked compact tension specimens (IT-CT) loaded at K rates of about 2×10^4 MPa$\sqrt{m}$/s on a servo-hydraulic machine using a damped set-up. A high frequency alternating current system (10 kHz) is used for the detection of subcritical crack growth during loading. The analog signals from the clip gage, load cell, ram travel and potential drop system are fed into a magnetic tape recorder, filtered and converted to digital data. Load-time and load-displacement-potential curves are plotted and analysed automatically by two different methods, according to the fracture mode :

- in the lower part of the transition curve, K_{ID} is calculated from the maximum load at failure in the linear elastic range (ASTM E399) ;

- in the transition and upper shelf regions, K_{JD} is calculated from J_{ID} at initiation of ductile crack growth in the elastic plastic range.

The experimental method described here is applied, as an example, to the study of a low-alloy, medium strength pressure vessel steel (A 508 Cl.3). A comparison is established between the toughness transition curves obtained under quasi-static (K_{Jc}) and dynamic (K_{JD}) conditions.

KEYWORDS

Dynamic fracture toughness ; J-integral ; CT specimen ; electrical potential method ; crack initiation ; crack growth ; A 508 Cl.3 steel.

INTRODUCTION

Low strength structural steels are generally temperature and loading rate sensitive. Results obtained some years ago by Barsom, Shoemaker and Rolfe (1970, 1971) showed that the most significant effect of increased loading rate is to shift the quasi-static K_{Ic} transition curve to higher temperatures. Moreover, Barsom (1970, 1975) and Roberts (1979) clearly demonstrated that the magnitude of the temperature shift between static loading ($\dot{\varepsilon} \approx 10^{-5}$ s-1) and dynamic loading ($\dot{\varepsilon} \approx 10$ s-1) appears to increase as the yield strength of the steel decreases. Although the strain rates generally imposed in service are relatively small or intermediate ($\dot{\varepsilon} \leqslant 10^{-3}$ s^{-1}), the dynamic fracture toughness K_{ID} determined by impact testing must be considered as a lower bound to ensure the safety and reliability of many large and complex steel structures (ship hulls, bridges, offshore drilling platforms, pressure vessels ...) in the hypothesis of an accident (collision, thermal shock ...) or exceptional events (earthquake, hurricane ...).

The experimental determination of dynamic fracture toughness K_{ID} following the guidelines of ASTM Method E399 often raises some technical difficulties. In spite of the improvement in the yield strength of the material with increasing strain rate, very large specimens must sometimes be loaded at $\dot{K}$ greater than 10^4 MPa$\sqrt{m}$/s using special testing facilities (Shabbits, 1970 ; Shoemaker, 1971 ; Logsdon, 1979). Many investigators are thus attempting to develop new techniques involving the use of smaller specimens capable of being tested at lower cost with conventional laboratory equipment. Experiments conducted in recent years by Begley and Landes (1972, 1976), Logsdon (1976), Marandet and Sanz (1977) in quasi-static conditions, demonstrated the ability of the J-integral method to evaluate fracture toughness K_{Ic} of steels in the transition temperature range. The same experimental techniques are used today to evaluate dynamic fracture toughness K_{ID} of medium-strength steels from the critical J_{ID} value determined with a single test specimen at the point of incipient crack growth, by an A.C. potential drop method.

EXPERIMENTAL METHODS

Specimen Preparation

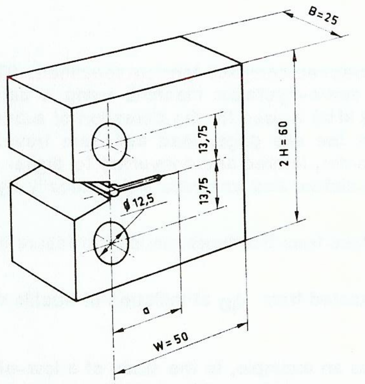


Fig. 1. Compact specimen geometry (CTJ 25).

Dynamic fracture toughness tests are performed on 25 mm thick precracked compact tension specimens (CTJ 25) having the dimensions shown in Fig. 1. The geometry is in general accordance with ASTM Method E399, except for the modification made to accomodate clip gages between two knives machined on the very axes of the loading pin holes.

The mechanical notch is extended by fatigue in accordance with ASTM recommandation, taking care to lower gradually the maximum applied load F_{max} so that the final stress intensity factor $K_{f\ max}$ does not exceed 24 MPa$\sqrt{m}$. The ratio of total crack length a (mechanical notch + fatigue precrack) to specimen width W is about 0.530.

High-Speed Loading and Impact Damping

Specimens are tested on a servo-hydraulic MTS machine with load frame and load cell capacities of 250 kN. Although the hydraulic system has a sufficient delivery (170 ℓ/min) to impart a maximum displacement ram speed $v_p \simeq 760$ mm/s over a calibrated travel of 100 mm, the tests must be carried out at a substantially lower speed (440 mm/s $< v_p <$ 650 mm/s) in order to avoid the resonance of the load cell. Loading rates in terms of $\dot{K}$ are of the order of 1.8 to $2.8 \cdot 10^4$ MPa$\sqrt{m}$/s in the elastic range.

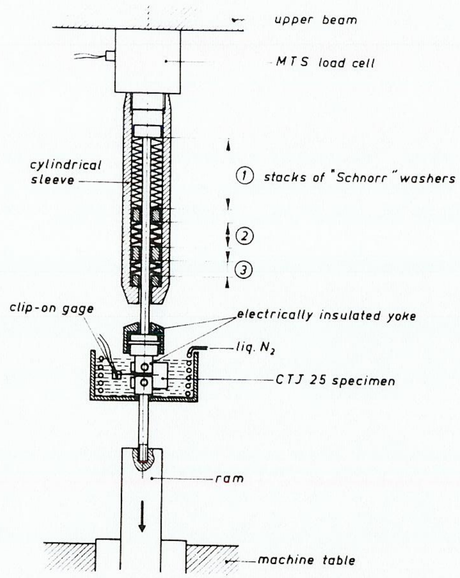


Fig. 2. High-speed loading and impact damping system.

The shock produced by the instantaneous deformation of the specimen is damped by means of a mechanical system consisting of a stack of truncated-cone washers. As shown in Fig. 2, the washers are grouped in three sets of different thickness in a cylindrical sleeve screwed onto the load cell. They flatten in deforming under the action of a cylindrical plate located at the end of the rod integral with the specimen and the ram in movement. This variable-rigidity device thus makes it possible to impart a rate of loading which increases in successive steps over a more or less large portion of the elastic range. The maximum loading rate is reached after the complete crushing of all the washers, when the specimen is connected to the ram moving at full speed.

Detection of Initiation

The A.C. potential drop method was developed at IRSID (Marandet and co-workers, 1977, 1978) in order to determine J_{Ic} at initiation of subcritical crack growth. A high frequency (10 kHz) current-regulated (3 A) differential microohmmeter is used to determine J_{ID} by means of a single specimen loaded in dynamic conditions (Fig. 3).

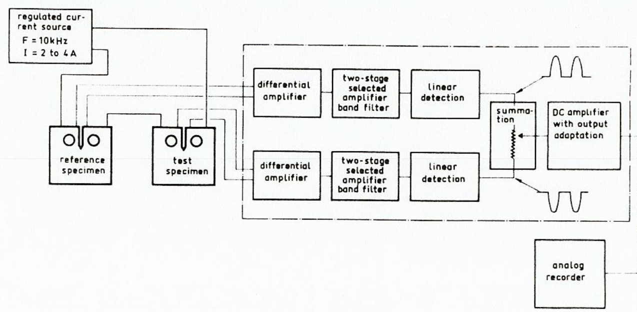
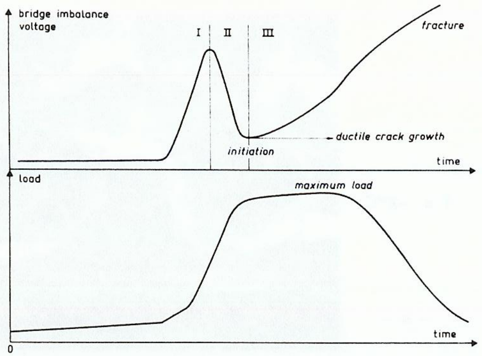


Fig. 3. Diagram of the circuit used to detect crack initiation under dynamic loading.



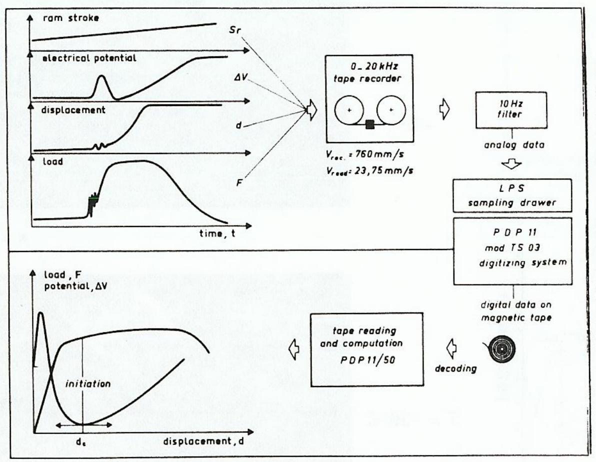
As stated previously, the load-potential-time curve can be divided in three regions (Fig. 4) :

- zone I : the increase of impedance is associated with the separation of the fatigue walls ;
- zone II : the decrease of impedance is associated with the inverse magnetostrictive effect ;
- zone III : the increase of impedance is associated with crack growth.

Fig. 4. Typical variations in the load and electrical potential recorded during high-speed straining of a specimen in ductile conditions.

Experimental evidence supports the hypothesis according to which the minimum of the electrical potential recorded between the zones II and III corresponds to the initiation of stable crack propagation in the specimen.

Recording and Processing of Signals



Electric signals proportional to the applied load F, load-point displacement d, imbalance voltage of the Thomson bridge ΔV, and ram stroke S_r, are recorded simultaneously as a function of time, filtered, converted into digital data and processed by computer in order to reconstitute the experimental diagrams showing the variations in the applied load F(daN) and in the imbalance voltage ΔV(mV) as a function of load point displacement d(mm). A schematic diagram of the processing system is given in Fig. 5.

Fig. 5. Schematic diagram of signal processing system.

The signals recorded on magnetic tape are spread over the time scale in a proportion equal to the ratio of the recording speed (v_{rec} = 760 mm/s) and the reading speed (v_{read} = 23.75 mm/s). The insertion of a lowpass filter with a level equal to 10 Hz or 100 Hz then makes it possible, in view of the amplification v_{rec}/v_{read} = 32, to eliminate the spurious oscillations having frequencies higher than 320 Hz or 3200 Hz. An LPS sampling drawer distributes the analog data to the

DEC PDP 11/03 computer which digitizes at the frequency of 2500 Hz. The digital data are stored on disc before being transmitted to a DEC PDP 11/50 computer. The interpretation of the diagrams plotted automatically finally makes it possible to calculate the values K_{ID}, J_{ID} or K_{JD} which characterize the fracture toughness of the material.

Interpretation of Experimental Diagrams

The dynamic fracture toughness under quasi-elastic plane strain conditions K_{ID} is calculated according to the ASTM E399-78 recommendation from the following expression :

$$K_{ID} = \frac{Fc}{B\sqrt{W}}\, f\left(\frac{a}{W}\right) \qquad (1)$$

where Fc = critical fracture load

B = specimen thickness

W = specimen width

a = average crack length measured at three points

$f\left(\frac{a}{W}\right)$ = dimensionless coefficient value given in a table for the specimen geometry

The dynamic fracture toughness under elastic-plastic plane strain conditions J_{ID} is calculated either at the initiation of fracture by cleavage or at the initiation of ductile crack growth, using the general expression proposed recently by Clarke and Landes (1979) from the original analysis of Merkle and Corten (1974) :

$$J_{ID} = \frac{A}{B(W-a)}\, g\left(\frac{a}{W}\right) \qquad (2)$$

where A = area under load vs load-point displacement record in energy units

$g\left(\frac{a}{W}\right)$ = dimensionless coefficient value that corrects for the tensile component of loading. Values are given in a table

The corresponding critical stress intensity factor K_{JD} is given finally by the well-known formula :

$$K_{ID} = \sqrt{\frac{E}{(1-\nu^2)}\, J_{ID}} \qquad (3)$$

where E = modulus of elasticity = 206.000 MPa

ν = Poisson's ration = 0.3

APPLICATION EXAMPLE

The test methods were implemented in order to determine the toughness transition curve under dynamic loading, K_{ID} or K_{JD}, of a ASME SA 508 Cl.3 steel typically used in forgings for nuclear pressure vessel applications such as shells, flanges, tube sheets and similar components.

Material

The test material is taken from a 230 mm thick forging nozzle. Chemical composition, heat treatments and mechanical properties determined transversely at one fourth of the shell thickness, are given in Table I.

TABLE I – Composition, heat treatments and mechanical properties of the ASME A 508 Cl.3 steel.

Chemical composition, weight percent										
	C	Mn	P	S	Cu	Si	Ni	Cr	Mo	Al
	0,150	1,31	0,0071	0,0064	0,060	0,32	0,74	0,23	0,51	0,0156

Heat treatment
875°C – 5h / Water quenched / Tempered 650°C – 6h / Air cooled and reheated slowly (30°C/h max.) to 550°C – 35h / Heated again slowly (30°C/h max.) to 615°C – 15h / Controlled cooled (30°C/h max.)

Tensile, drop weight and Charpy properties							
σ_{ys} (MPa)	σ_{ut} (MPa)	Elongation (%)	Reduction of area (%)	T.T. 28J (°C)	FATT (°C)	Upper shelf energy (J)	NDTT (°C)
476	602	23.5	68.5	-48	+15	198	-35

σ_{ys} = 0,2 % Yield Strength ; σ_{ut} = Ultimate Tensile Strength. Room Temperature.

Results of Tests Conducted under Dynamic Conditions

The tests were carried out using CTJ 25 specimens precracked by fatigue and loaded under dynamic conditions ($\dot{K} \sim 1.8 \times 10^4$ MPa $\sqrt{m}$/s) at six different temperatures between -91°C (NDTT -56) and +61°C (NDTT +100).

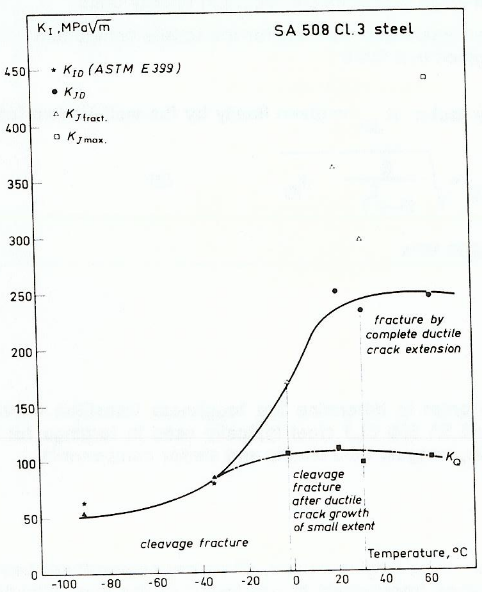


Fig. 6. Variation in dynamic fracture toughness K_{ID}, J_{JD}, K_J fract. and K_J max. as a function of temperature.

The dynamic fracture toughness transition curve, K_{ID} or K_{JD}, can be subdivided into three distinct regions, each characterized by a particular fracture mode (Fig. 6) :

- at temperatures lower than about 0°C, brittle fractures by cleavage always occur under elastic conditions in the zones I or II of electrical potential variation (Fig. 7-a). Critical K_{JD} values calculated by the J-integral method are in good agreement with the K_{ID} values calculated directly in accordance with the experimental standard ASTM E399. The mechanism of decohesion by cleavage is initiated in the stretched zone at the front of the fatigue crack without any substantial amount of ductile extension ;

- at temperatures higher than about +40°C, the fractures exhibit a clearly ductile nature. The crack is initiated at the minimum electrical potential variation, i.e. well before the maximum of the loading diagram. It then propagates continuously until the complete decohesion of the ligament and the saturation of the Thomson bridge (Fig. 7-b). The initiation is characterized by a critical value of $K_{JD} \simeq 250$ MPa $\sqrt{m}$ which constitutes an upper limit for the type of specimen used (Marandet, Phelippeau, Rousselier, 1980). The mechanism of decohesion by the coalescence of microcavities leads to ductile crack propagation which appears in the form of dimples of varying size over the entire fracture surface.

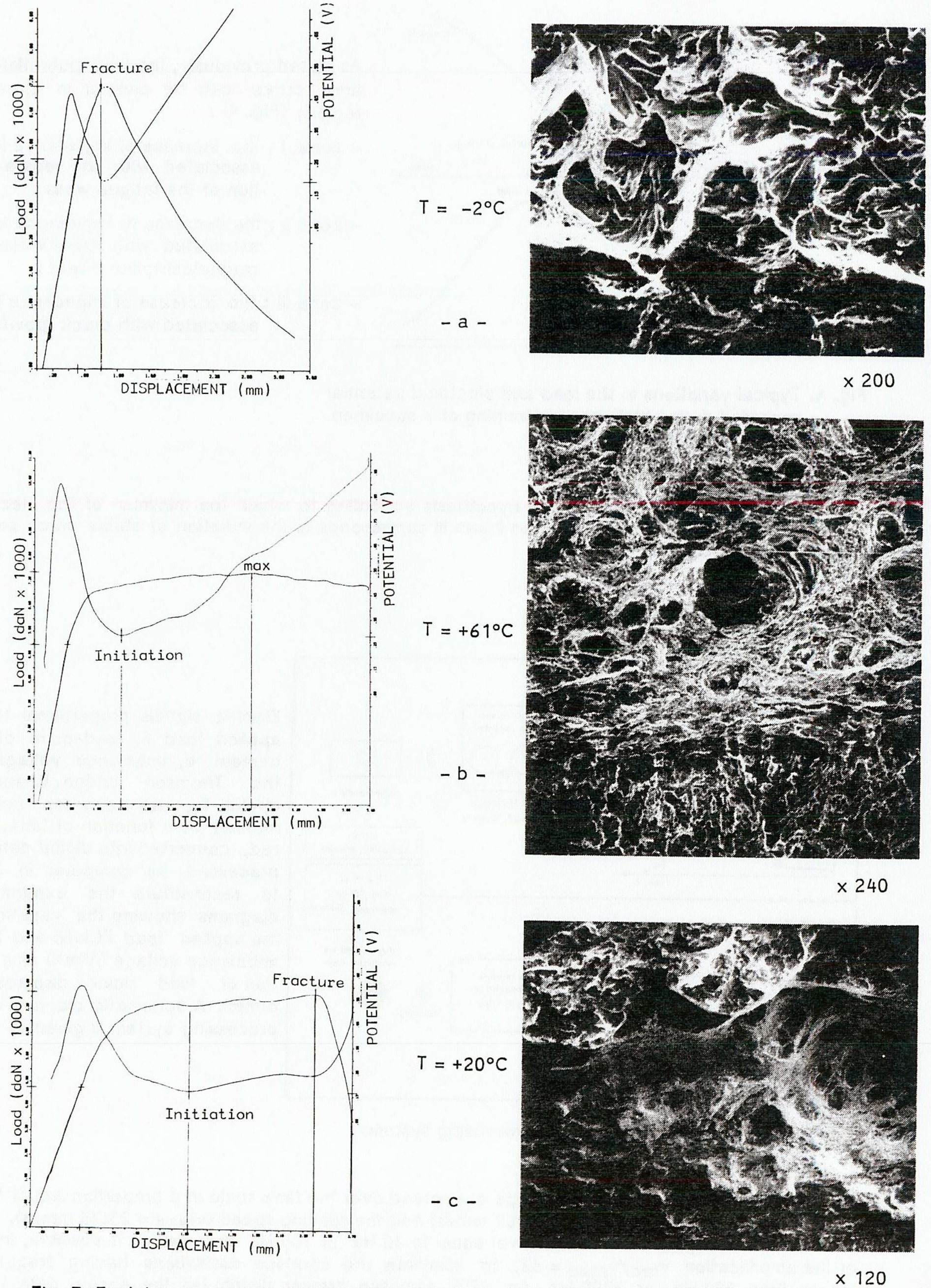


Fig. 7. Evolution of fracture mode under dynamic loading at three different temperatures.

- finally, in the temperature interval between 0 and +40°C, sudden fractures by cleavage occur under elastic-plastic conditions in the zone III of electrical potential variation, i.e. after a certain stable crack growth by ductile extension (Fig. 7-c). The K_{JD} values determined upon initiation are moreover very close to those determined at the upper shelf. The mechanism of decohesion by cleavage is initiated here during ductile crack growth which appears, on the fracture surface, as a narrow strip of dimples separating the fatigue crack from the brittle fracture faces.

Comparison with Rèsults Obtained under Quasi-Static Conditions

The toughness transition curves, K_{Jc} and K_{JD}, established respectively under quasi-static ($\dot{K} \sim 1$ MPa$\sqrt{m}$/s) and dynamic conditions ($\dot{K} \sim 1.8 \times 10^4$ MPa$\sqrt{m}$/s) are given in Fig. 8. The increase in the strain rate at the crack tip brings about two contrary effects depending on the nature of the decohesion mechanism :

- reduction in toughness of the material within the range of sudden fractures by cleavage, the offset ΔT_V of the static K_{Jc} and dynamic K_{JD} toughness transition curves being of the order or 75°C at the level of K_J = 100 MPa$\sqrt{m}$;

- a substantial increase in the toughness of the material within the range of unstable fractures by ductile crack growth, the rise in the ductility shelf from $K_{Ic} \sim 220$ MPa$\sqrt{m}$ to $K_{JD} \sim 250$ MPa$\sqrt{m}$ being related to the increase in yield strength.

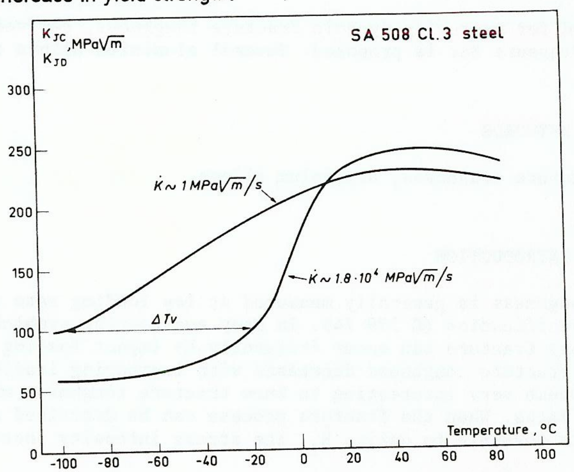


Fig. 8. Fracture toughness transition curves established under quasi-static (K_{Jc}) and dynamic (K_{JD}) conditions.

CONCLUSIONS

The experimental determination of J_{Ic} under dynamic loading (J_{ID}) calls for the use of extensive equipment facilities : a powerful and fast tensile testing machine, a system for damping upon loading, and finally a data acquisition and processing system. However, the main technical difficulty consists in detecting, during loading, the stable crack extension taking place at the front of the fatigue crack. The apparatus we have developed for this purpose is a differential microohmmeter which operates under high frequency-low intensity alternating current. Crack initiation and propagation cause a variation in the electrical potential, thus making it possible to determine the critical value J_{ID} through a single test.

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