Basic Principle of Dynamic Fracture Toughness Evaluation by Computer Aided Instrumented Impact Testing (CAI) System

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ABSTRACT

Dynamic fracture toughness testings have been carried out on some industrial ductile materials and brittle ones using a newly developed computer aided instrumented impact testing (CAI) system. Fracture behaviours are examined and discussed for some subjects such as crack initiation, blunting process, true fracture loading, stress intensity rate and so on. The CAI system is expected as a rapid and inexpensive method to measure the fracture toughness of materials in dynamic loading condition.

KEYWORDS

CAI system; dynamic fracture toughness; crack initiation point; blunting process; true fracture loading; stress intensity rate

INTRODUCTION

The Charpy impact test has come into wide use as a convenient method to evaluate the toughness of materials. The method, however, has kept less importance because the Charpy V impact values obtained by this method have no more significance other than as screening ones; while the fracture mechanics analysis has advanced remarkably. After long years of study, one of the authors has succeeded recently in obtaing the dynamic elastic-plastic fracture toughness (J_d) and the tearing modulus (T_{mat}), that is the crack propagation resistance, by novel means of analysing the load-deflection (or time) record measured on a single Charpy type specimen with precrack using a computer aided instrumented Charpy impact test for ductile materials such as metals (Kobayashi et al., 1986a, 1987a). Besides, for the brittle materials like ceramics, a process to analyze the effective value of dynamic fracture toughness (K_{Id}) has been also developed (Kobayashi et al., 1986b). This evaluation is characterized by a rapid and simple way to measure the fracture toughness under the strict condition of dynamic loading (Kobayashi et al., 1988). Therefore, some recent informations for the dynamic fracture toughness are reported in this paper including accounts of several important points of the CAI system.

ANALYSIS FOR DUCTILE MATERIALS

Modification of wave shape

When the hammer collides with a test specimen, the specimen is suddenly accelerated and happens to oscillate by the effect of the inertial loading. During the slow crack speed in ductile fracture of metals, it may be thought that the mean level of oscillation reflects the true load. The author has developed the travelling mean method to modify the load-deflection curve with oscillation component (Kobayashi, 1984a).

Detection of crack initiation point

One of the authors has developed a stop block method (Kobayashi, 1984) (with multiple specimens) to stop the hammer forcedly and verified on many materials that the crack begins to grow when an increase is recognized in the changing rate of assumed elastic compliance (Kobayashi et al., 1986a, 1988). Fig.1 shows a result obtained in A508 Class 3 steel. It is seen that the crack initiation position detected by this method corresponds to the maximum point of blunting of crack tip (SZW_c). Moreover, this crack initiation point has been confirmed to agree with one by the electrical potential method in the static test (Niinomi et al., 1986). Measuring the true value of absorbed energy up to the crack initiation point, E_i (equals to the apparent one of E_i' multiplied by C_s/C_t; C_s and C_t are respectively the specimen and the system compliances, and are so susceptible to the strain rate (as will be stated later)) makes it possible to calculate easily the dynamic elastic-plastic fracture toughness J_d, from using the Rice's equation. Validity and specimen size effect on obtained J_d values have been reported elsewhere (Kobayashi et al., 1988).

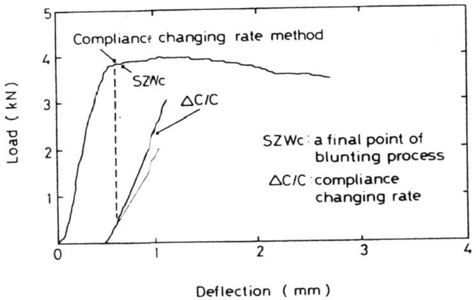


Fig.1 Curves of load-deflection and compliance changing rate-deflection. (A508 Cl 3)

Prediction of crack growth by the key curve method and J_R curve

Applying the n-th power law, the relation between the load (P) and the plastic deflection (Δ_{pl}) is approximately presented in the next equation.

$$(PW/b_o^2)=k(\Delta_{pl}/W)^n \tag{1}$$

where k and n are constants, b_o is initial ligament width and W is specimen width.

The constants k and n are obtainable in the plotting of both terms in eq.(1) on logarithmic graph. Then, the amount of crack growth, Δa, can be estimated in the following form;

$$\Delta a=W-[(PW^{n+1}/k\Delta_{pl})^{1/2}+a_o] \tag{2}$$

where a_o is initial crack length.

The J_R curves predicted from this method have been already ascertained to agree with measured values on various materials in the stop block method (Kobayashi et al., 1986a, 1988).

Blunting process of dynamic crack and its evaluation

As mentioned above, it is thought that the compliance changing rate method provides the initiation point of crack growth corresponding with the blunting end point, so it is important to clarify the blunting process under the dynamic loading.

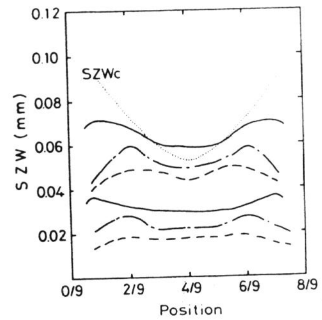


Fig.2 The blunting process of the crack tip.

Using the stop block testing method, the standard size Charpy specimens with fatigue crack (a/W=0.6) were tested up to various amounts of deflection under the dynamic loading to measure the change of the stretch zone width (SZW) at the tip of the precrack by means of SEM observation. The result obtained is shown in Fig.2. The blunting process of dynamic crack tip may be considered as follows. In the early stage of blunting, the crack tip gets dull nearly homogeneously in the direction of the crack width, and the front edge of crack is almost flat. According to advance of the deformation, however, SZW shows a large increase in the positions 1/9, 2/9, 6/9 and 7/9 of specimen width. On the other hand, in the center positions of 3/9, 4/9 and 5/9, the deformation i.e., the development of SZW is intensely constrained because the stress triaxiality in this region is larger than in the sides. Since the SZW in the center is less than ones in sides, the geometry of SZW in the front edge of precrack approaches a concave shape with advancing of the crack blunting process.

Moreover, the critical stretch zone width (SZW_c) shown in the U-shaped curve in the figure was obtained in completely fractured specimen. Consequently, the initiation of cracking takes place firstly in the center of the specimen.

Blunting line

The following equation is given as a blunting line in ASTM E813;

$$J=2\sigma_{fs}SZW \qquad (3)$$

where σ_{fs} is the static effective flow stress ($\sigma_{fs}=(\sigma_{ys}+\sigma_B)/2$, σ_{ys} the static yield stress and σ_B the static tensile strength). However, some discrepancy from eq.(3) is reported for several steels and aluminum alloys (Zu-han Lai, 1985). Eq.(3) is only applied in the condition of the static loading, and there is little report about the blunting line under the severer condition of the dynamic loading (Blumenauer, 1986). Then, in the present study, the blunting lines were measured in both the static and the dynamic loading conditions. This is shown in Fig.3. The coefficient is about 3 under the static loading test. σ_{fd} is the dynamic flow stress which is calculated from the dynamic bending yield load (Py) and the dynamic bending maximum load (Pm) using the Server's equation (Kobayashi, 1984b, Server, 1978). If σ_{fs} is used to represent the equation of the dynamic blunting line, the coefficient become about 1.5 instead of 1.1.

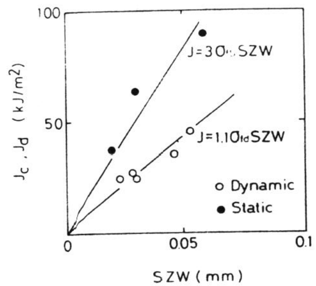


Fig.3 The blunting line under the static and dynamic loading conditions.

The profiles near the crack tip tested under both conditions of the static and the dynamic loading are schematically shown in Fig.4 to measure the crack tip opening angle (β). The values obtained are respectively 45 and 31 deg. This is due to the triaxiality and the plastic constraint near the

crack tip. This phenomenon may be related to the abnormal size effect reported by Kobayashi et al. (Kobayashi et al., 1988).

(a) static condition (b) dynamic condition

Fig.4 The crack tip geometries and crack tip opening angle.

ANALYSIS FOR BRITTLE MATERIALS

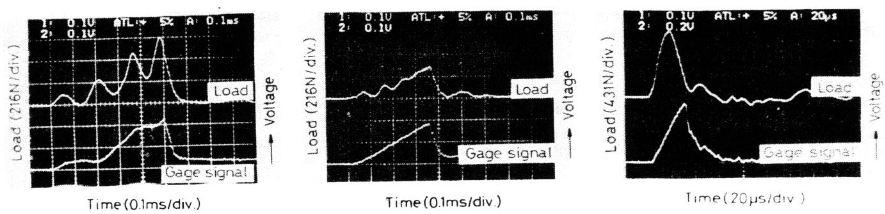
Measurement of dynamic fracture toughness

In brittle materials such as ceramics and plastics in which low stress brittle fracture takes place before yielding, it is very much more difficult to estimate the true value of fracture load because of the marked oscillation caused by the inertial effect. In such case, the period of the normal oscillation of stress wave, τ, is given in the following empirical equation.

$$\tau=1.68(SWEBC_s)^{1/2}C_o \qquad (4)$$

where C_o is sound speed in specimen , C_s is specimen compliance, B is specimen thickness, E is Young's modulus, W is specimen width and S is span distance.

It is almost possible to measure a true fracture load in the low velocity impact test with fracture time interval of $t_f \geq 3\tau$. This procedure is recommended by Server (Server, 1987). However, it is recommened for the test to be conducted in the condition of applied energy $E_o \geq 3E_t$ (E_t is the total absorbed energy). The authors have proved this relation is also applicable to ductile fracture (Kobayashi et al., 1987a).



V_o=0.57m/s, B=15mm (a) V_o=0.57m/s, B=10mm (b) V_o=4.28m/s, B=10mm (c)

Fig.5 Typical load-time curves for epoxy resin.

Fig.5 shows typical examples of load-time curve for an epoxy resin filled with 64% SiO_2 particles in testing with two kinds of specimen geometry and impact velocity (V_o), where the upper wave record is the output signal from the load-cell on the hammer and the lower one is the output from the gage put directly on the specimen. The specimen sizes are W=B=15mm and S=60mm in (a), and W=B=10mm and S=40mm in (b) and (c). It is recognized that the recording of curve with little influence of oscillation is realized in the low velocity impact test on a small size specimen according with the descent of τ. Moreover, C_s shows a strain rate dependency in such brittle materials too (Kobayashi et al., 1988). The authors have recently represented the dynamic C_s as the following equation.

$$C_s=\frac{S^2}{EBW^2}\left\{Y+0.29\frac{W^2}{(W-a)^2}(\log(1/V_o)-0.339)\right\} \tag{5}$$

$$Y=27.11(a/W)^3-8.56(a/W)^2+1.77(a/W)+0.829 \tag{6}$$

This equation has been confirmed to be also applicable for ductile materials.

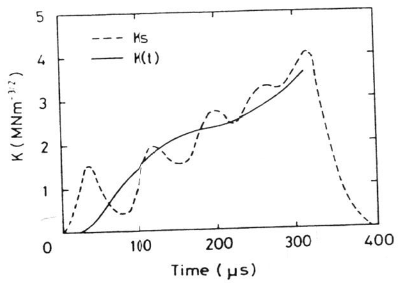


Fig.6 Time variation of dynamic stress intensity factor K_s, K(t).

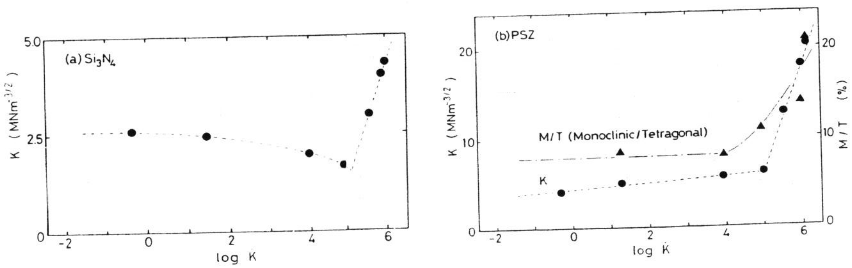


Fig.7 Change of fracture toughness with stress intensity rate $\dot{K}$ in ceramics.

In case of a low velocity impact test, it is possible to conduct the following Kishimoto's analysis in the CAI system. Kishimoto et al.

(Kishimoto et al., 1980) have proposed the formula to yield time change of the dynamic stress intensity factor, K(t), in considering such an inertial effect on modeling Timoshenko's bar . It is shown in Fig.6 obtained in the test for the same epoxy resin as provided above that K(t) gives a change corresponding to about mean level of oscillation in which K(t) is compared to the change of K_s, of the hammer output signal. If fracture initiated at the maximum point of K_s curve, the dynamic value of K_{Ic}, that is K_{Id}, corresponds to that value of K_s. Though the impact speed V_o is low in this case, it is pointed out that true K_{Id} is impossible to be measured when V_o is high, because a phenomenon of loss of contact takes place by means of vibration effect among hammer, specimen and anvil. Moreover, the maximum load point gives no coincident with the fracture initiation one (Kalthoff, 1985, Kobayashi et al., 1987b).

By the way, to obtain the dynamic value of K_d under the dynamic loading with high speed impact, the impact response curve method proposed by Kalthoff (Kalthoff, 1985) is accepted as the most appropriate procedure. As a variation of this method, there exists the small gage method, where a small gage is put directly just beside of the crack tip on the specimen surface; although this is still within a region of experimental one with troublesome.

Further, it has been recognized in experiments using this way that Si_3N_4 (silicon nitride) shows a tendency of K_d to increase rapidly after taking a minimum with the stress intensity rate $\dot{K}$ ($=K_d/t_f$); see Fig.7 (a). Kalthoff has reported such a phenomenon with an explanation of incubation time (Kalthoff, 1985). On the contrary, PSZ (partially stabilized zirconia) has shown a tendency of K_d to increase simply with $\dot{K}$. In this case it is concluded that such tendency of the change about the amount of stress induced transformation (tetragonal (T) to monoclinic (M) phase transformation) may be related to the trend of K_d; see Fig.7 (b).

Energy analysis of unnotched specimen on instrumented Charpy test

The authors have also proposed a simple method to estimate the true fracture energy, E_f, of the specimen itself for unnotched specimen in CAI system (Kobayashi et al., 1986b, 1987b). This method is effective as a screening test. On the Charpy test for the brittle materials, an excess loss in energy in addition to fracture the specimen is so large that the meaning of measured value itself does not become clear. Then, the total energy, E_t, is divided into such components as follows;

$$E_t=E_s+E_m=E_f+E_k+E_m \tag{7}$$

where E_s and E_m are the energy stored in the specimen and in the testing machine respectively. E_s is further divided into the true deformation and fracture energy of the specimen, E_f, and the one spent for the toss of broken halves, E_k. An influence of impact speed on E_f for PSZ is shown in Fig.8. It is seen that E_f decreases after reaching a maximum value in increasing impact speed, V_o, which differs from a tendency of change with $\dot{K}$ in fracture toughness test. The amount of stress induced transformation products shows the same tendency as this. Though the toughness is improved by the stress induced transformation in lower range of impact speed, it is presumed that an early release of stress is caused by the remarkable occurrence of microcracks owing to the over loading effect in the unnotched specimen in higher impact speed range.

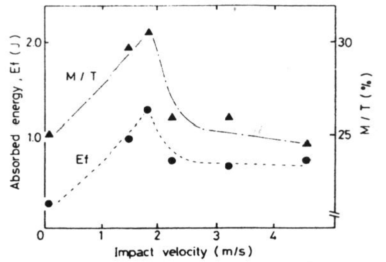


Fig.8 Change of absorbed energy and stress induced transformation ratio with impact velocity in PSZ.

CONCLUSION

Some evaluations of fracture toughness for a number of materials such as metals, ceramics and plastics have been presented using a novel instrumented Charpy impact testing system. This method is rapid and inexpensive to evaluate dynamic fracture toughness parameters and recently in advance toward practical use as a computer aided instrumented Charpy impact testing (CAI) system (Kobayashi et al., 1988) in Japan.

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