EXPERIMENTAL DETERMINATION OF HIGH LOADING RATE EFFECTS ON FRACTURE TOUGHNESS OF ALUMINIUM ALLOYS

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ABSTRACT

A new method for measuring dynamic fracture toughness, derived from the Split Hopkinson Pressure Bar is proposed. Several aluminium alloys are tested.

KEYWORDS

Dynamic fracture toughness, aluminium alloys.

INTRODUCTION

Fracture toughness is generally measured at low loading rate according to ASTM Standard Specification (E 399 74). In many engineering problems (transport, energy applications) fracture can occur frequently by impact loading. For rate sensitive materials, fracture toughness decreases with increasing loading rate, and for this reason it seems very interesting to know fracture toughness within a large spectrum of loading rates. When the fracture process can be described as a linear elastic event, it is possible to define $\dot{K}_I$, the stress intensity factor rate :

$$\dot{K}_I = \frac{K_{Ic}}{t_c} \qquad (1)$$

t_c : fracture time ; K_{Ic} : critical stress intensity factor ; $\dot{K}_I$: stress intensity factor rate. $K_{Ic} = f(\dot{K}_I)$ is used for dynamic fracture toughness and $K_{Id} = f(\dot{a})$ for the toughness related to a crack propagating at a rate of $\dot{a}$..

The loading rate spectrum can be divided into three regions :

- part I : quasi-static rupture - $10^{-3}\,\mathrm{MPa\sqrt{m}/s} \leq \dot{K}_I \leq 10^{3}\,\mathrm{MPa\sqrt{m}/s}$

In this range tests are performed with conventional tensile machines or closed loop machines ;

- part II : dynamic fracture - $10^{3}\,\mathrm{MPa\sqrt{m}/s} \leq \dot{K}_I \leq 10^{5}\,\mathrm{MPa\sqrt{m}/s}$

This is the range where instrumented sharpy machines are in use.

- part III : high speed loading rupture - $10^6 \mathrm{MPa}\sqrt{m}/s \leq \dot{K}_I \leq 10^9 \mathrm{MPa}\sqrt{m}/s$

In this region, it is necessary to use a stress wave loading system.

Earlier experimental work on dynamic fracture toughness was carried out by Kraft and Sullivan (1963), Radon and Turner (1966). Later Shabbits (1970) and also Ireland (1976) presented a $K_{Ic} = f(\log \dot{K})$ diagram on A 533 B steels for $\dot{K}_I$ values up to $10^5 \mathrm{MPa}\sqrt{m}/s$.

Costin, Duffy and Freund (1977) have developped an experimental method to obtain $\dot{K}_I$ values higher than $10^6 \mathrm{MPa}\sqrt{m}/s$. The notched and prefatigued section of a long bar specimen is loaded, in this method, to failure by the rising portion of an incident tensile wave. The incident wave is generated by an explosive. This method was derived using the "Split Hopkinson Pressure Bar" due to Kolsky (1949) (SHPB).

In this paper, a new method is applied which is also based on the SHPB application, but small and cheap samples are used. The method was proposed by Klepaczko (1979). This method was employed in this paper to characterize some aluminium alloys within a large spectrum of loading rate.

WEDGE LOADING CT SAMPLE FOR DYNAMIC TOUGHNESS MEASUREMENT

Wedge loaded samples derived from the classical compact tension specimen (CT) were used for fracture toughness measurements in quasi-static and dynamic situations.

The wedge loaded CT sample (WLCT) is similar to classical CT one. The part before pin holes is cut off, as shown in figure 1, and an angular incision is milled to accommodate the wedge.

The dimensions of specimens are $2\,H_1 = W_I = 20$ mm.

These small dimensions allowed the short fracture time to be completed within 10 waves reflections between the free surfaces of such specimens. Thus it is possible to use the quasi-static solution for the fracture toughness measurement.

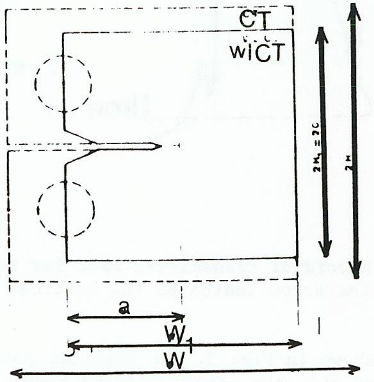

Fig. 1. Geometry of WLCT sample

$$K_{Ic} = \frac{F_c}{B\sqrt{W}} \; f \, \frac{a}{W} \tag{2}$$

where F_c : critical force, $f \frac{a}{W}$: compliance function, B, W : thickness and width.

Influence of Dynamic Frictional Effect

In the used method, the loading is produced by an incident wave through a carbide wedge with a 45° angle. Wedge loading is necessary to load the sample in tension with the compressive wave. The angular slot in the sample body has 43°. This small difference gives a small contact area along the edge lines between the wedge and sample. Consequently, the effect of friction must be taken into account and the loading tensile force is influenced by the friction coefficient μ. The relation between the critical compressive load P_c and the critical tensile force F_c is given by :

$$F_c = \frac{P_c}{2\mathrm{tg}\,\frac{\alpha}{2} + \beta} \tag{3}$$

$$\alpha : \text{wedge angle and } \beta = \mathrm{tg}^{-1}\mu \tag{4}$$

The coefficient of friction is usually measured in the static situation, using the known stiffness of the WLCT sample. This coefficient must be measured under the same lubrication conditions as occuring during experiments. For aluminium alloys and for lubrication with MoS_2, an average value of μ is 0.1. This value is assumed to be identical to that one in dynamic situation according to Klepaczko and Malinowski (1977).

Compliance of WLCT Sample

The compliance function Y = f(a/W) was computed using a finite element method, and some experimental verifications were also carried out. The compliance function is given by the equation (5)

$$Y(a/W) = 4.11 - 1.83(a/W)^{1/2} + 21.13(a/W)^{3/2} + 11.44(a/W)^{5/2} + 18.61(a/W)^{7/2} \tag{5}$$

Fatigue Precracking

The sample geometry makes fatigue precracking possible with the same wedge as used for the fracture test using a standard closed loop testing machine. The precracking conditions were as flollows : load ratio $R_s = 0.1$, frequency f = 60 Hz, crack length $\Delta a = 3$ mm.

EXPERIMENTAL METHOD FOR QUASI-STATIC AND DYNAMIC FRACTURE INITIATION

Quasi-static Loading

As indicated above, the same wedge loading method and the same geometry of the sample are used for static and dynamic tests. For quasi-static loading, a special apparatus was used.

Dynamic Loading and Modified SHPB Apparatus

This apparatus is based on the "Split Hopkinson Pressure Bar" concept due to Kolsky

(1949). The application of the SHPB to fracture dynamics has been proposed by KLEPACZKO (1979). The system consists of three parts : air gun, instrumented Hopkinson bar, electronic recording system.

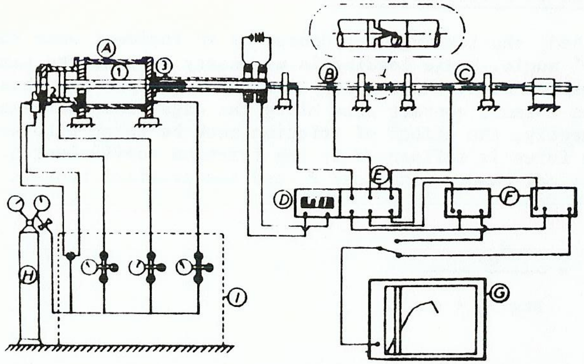

Fig. 2. Apparatus for dynamic fracture tests

The WLCT sample ⑦ is inserted in between the incident wave bar Ⓑ and the transmission wave bar Ⓒ . The wedge is glued to the incident bar and inserted into the WLCT incision. The incident loading wave is generated by projectile impact on to the incident bar. This projectile is accelerated to a desired speed with air gun Ⓐ . The principle of operation of the air gun is as follows : the pressure in the main chamber ① is supplied by a pressure source Ⓗ . Pressure acting on the rear chamber ② locks the chamber ① . By opening the rear valve of chamber ② , the piston moves rapidly, and pressure in chamber ① accelerates the projectile ③ . The impact speed of the projectile is measured by an electronic timer D . This timer starts and stops by two electrical signals emitted by two photodiodes. During the projectile passage, lightrays are cut, and the impact speed is thus measured.

The projecile speed is set by the pressure level in the main chamber or projectile length. The pressure can be changed within wide limits, applied projectile lengths are between 100 and 350 millimeters.

The projectile impact generates a compressive incident wave which propagates along the incident bar and is measured by the strain gauge. The transmitted compressive wave is measured with a second gauge placed on transmitted bar. Two channel amplifiers are necessary to monitor the amplitudes of incident, reflected and transmitted waves which is accomplished by two "Biomation 805" transient numerical recorders Ⓕ and a XY recorder Ⓖ .

Critical Load Determination

The critical compressive load P_c can be measured on the transmitted wave when equilibrium of forces between both bars can be assumed.

The complete record of dynamic experiments yields ε_1, ε_R and ε_T, i.e. the strain amplitude of the incident, reflected or transmitted waves. It can be shown that the load is proportional to the transmitred wave $\varepsilon_T(t)$ (Klepaczko, 1979), thus

$$P_c(t_c) = ES.\varepsilon_T^c(t_c) \qquad (6)$$

E : Young modulus, S : section of bars, t : time, Subscript c indicates critical value.

A dynamic calibration of the strain gauge recording is directly offered by measurement of the projectile speed.

The stress generated by impact is given by :

$$\sigma = \rho c_o v_o \qquad (6)$$

v_o : projectile speed, ρ : density of bar material, c_o : wave velocity.

Using Hooke's law, the calibration formula can be written :

$$\varepsilon_I = \frac{1}{2} \frac{D_P^2}{D_H} \frac{v_o}{c_o} \qquad (7)$$

ε_I : incident wave amplitude, D_P : projectile diameter, D_H : bar diameter.

Such a calibration is performed without samples and with incident and trasmitter bars in contact.

Oscillogram Examination

The critical load P_c is generally easily detected by "pop-in" or by the maximal value of $\varepsilon_T(t)$. After the measurement of ε_T and t_c, the necessary values of P_c and F_c can be calculated from (3) and (6) to obtain K_{Ic} and $\dot{K}_I$.

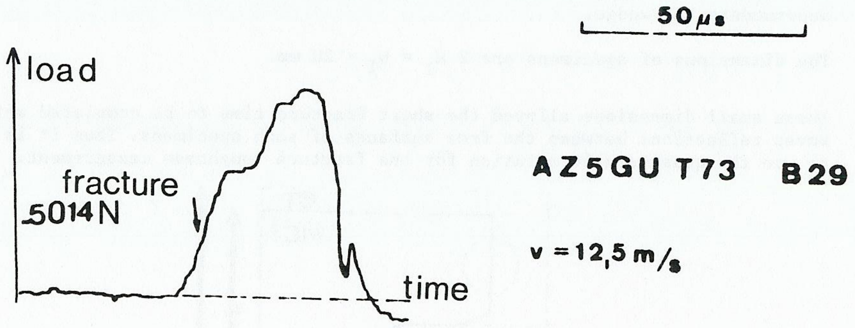

Fig. 3. Record of transmitted wave for aluminium alloy : the arrow indicates the critical load (5014 N).

A typical record is shown in Fig. 3. The critical point where the crack starts to propagate is indicated with the arrow. Time to rupture is about 16 µs. Fracture occurs generally in linear where the wedge is moving at constant speed. The procedure of "5 % offset" is used when any "pop-in" point cannot be easily detected.

The plot of $K_{Ic} = f(\dot{K})$ diagram for a wide spectrum of loading rate, $1\ \text{MPa}\sqrt{m}/s < \dot{K}_I < 10^6\ \text{MPa}\sqrt{m}/s$ (Fig. 5) was obtained for PA6 alloy by Klepaczko (1979).

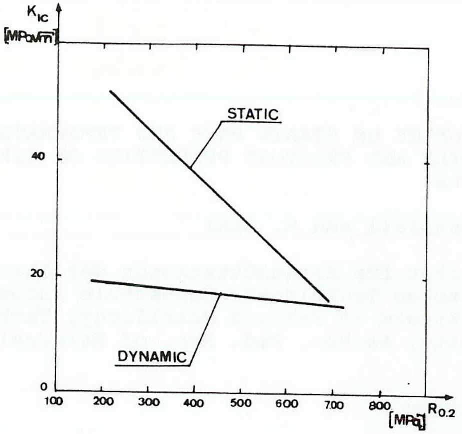

Fig. 4. Variation of fracture toughness in aluminium alloys with yield strength $R_{0.2}$ and loading rate $\dot{K}_I$.

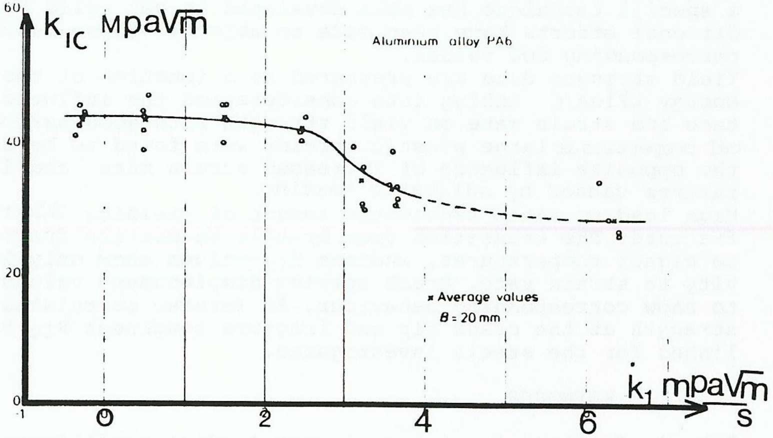

Fig. 5. Fracture toughness K_{Ic} versus loading rate K_I for aluminium alloy PA6.

This curve presents a transition of K_{Ic} at $\dot{K}_I \simeq 10^3$ to $10^4\ \text{MPa}\sqrt{m}/s$ and the minimum value of K_{Ic} is obtained for $\dot{K}_I = 10^6$ to $10^7\ \text{MPa}\sqrt{m}/s$. Transition occurs probably at the transition of isothermal to an adiabatic process. At high loading rates crack tip heating during the fracture process gives an increasing of toughness but not enough to balance the strain rate in aluminium alloys. Fractographic examination by scanning electron microscopy indicated that the average dimple size decreased at high rate of loading.

FRACTURE TOUGHNESS IN QUASI-STATIC AND DYNAMIC SITUATION FOR ALUMINIUM ALLOYS

Five aluminium alloys were tested in dynamic and static conditions. These five alloys are called Pa6, K63, AZ5G, AZ5GU, AZ8GU.

A thermal treatment allowed to vary the yield strength between 300 and 700 MPa. Mechanical properties and fracture toughness are given in Table I.

TABLE I Yield Strength and Fracture Toughness

	PA6	K63	K63	AZ5G	AZ5G	AZ5GU	AZ5GU	AZ8GUZr
Thermal treatment	as received			T6 aff	T6	T73	T6	T6
σ_y, MPa	405	500	520	250	320	420	500	690
σ_{ul}, MPa					980	490	580	730
K_{Ic}, MP√m $\dot{K}_I = 1\text{MPa}\sqrt{m}/s$	45	29.7	21.8	51	33	31	29.5	16.2
K_{Ic}, MPa√m $\dot{K}_{Ic} = 10^6\text{MPa}\sqrt{m}/s$	28	19	17.1	18	17	18.5	17.7	13.5
ΔK_{Ic} %	-38%	-36%	-21%	-65%	-49%	-41%	-47%	-17%

Results for fracture toughness measurements are plotted as $K_{Ic} = f(R_{0.2})$ diagram, (Fig. 4). In all cases, fracture toughness is lower in dynamic conditions ($\dot{K}_1 = 10^6\text{MPa}\sqrt{m}/s$) than in static conditions ($K = 1\ \text{MPa}\sqrt{m}/s$). The fracture toughness dependance on yield strength is less pronounced in dynamic conditions. Loss of toughness is higher for the low strength alloy (65 %). For high strength alloy it is only 17 %. Scatter in tests results is about 20 %.

DISCUSSION

The most frequently published results on dynamic fracture toughness, say for $\dot{K} < 10^4\ \text{MPa}\sqrt{m}/s$, show that fracture toughness decreased with increasing loading rate. Some contradictions are generally associated with instrumented hammer techniques.

Dynamic initiation of fracture involves two important questions :
- what is the value of $\dot{K}_I$ to get a minimum of fracture toughness K_{Ic} ?
- what kind of physical process explains this loss of toughness ?

CONCLUSIONS

An original apparatus is built as proposed by Klepaczko (1979) to measure fracture toughness at high crack tip loading rates up to $K_I \gg 10^6$ MPa$\sqrt{m}$/s.

This apparatus is based on "Split Hopkinson Pressure Bar " concept due to Kolsky (1949).

Special WLCT sample was designed for this purpose. The critical fracture load is measured from the transmitted wave taking into account the coefficient of friction.

Fracture toughness of aluminium alloys decrease at increased loading rates. The decrease of toughness is more substantial for low strength alloys.

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