FRACTURE INITIATION OF METALS AT HIGH LOADING RATES

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ABSTRACT

The purpose of this paper is to present a new experimental procedure which allows the determination of the fracture parameters of metals at very high loading rates. Using stress wave loading, a tensile stress pulse is applied on a notched pre-cracked bar providing the rupture. The duration of a test is about 20 µs, and the range of loading rates lays between 10^6 and 10^8 MPa $\sqrt{m}$ s^{-1}. By recording load-time and crack opening displacement-time variations, K_{Ic} (for brittle materials) or J_{Ic} (for ductile materials) can be determined. In application of this technique, some results on a 35 NCD 16 steel are presented.

KEYWORDS

Experimental technique, Dynamic loading.

In most cases the fracture initiation in metals is regarded as occuring under static or quasi-static loading conditions. However, many loading conditions occur in practice which cannot be treated as quasi-static and in these cases, the inertia of the material as well as its strain-rate sensitivity must be taken into account. For this reason, the fracture initiation resulting from the application of dynamic loads has received considerable attention in recent last years.

Different approaches to dynamic testing have been performed. One of them is the instrumented Charpy test which permits to reach loading rates of about 10^5 MPa $\sqrt{m}$ s^{-1} and provides useful data to fracture theories. However, there are some disadvantages, particulary in the knowledge of the state of stress which is difficult to determine on account of reflected stress waves in the specimen and the apparatus.

Krafft (1964) and Eftis and Krafft (1965) proposed another approach. Performing tests with loading rates up to 10^3 MPa $\sqrt{m}$ s^{-1} and using strain hardening characteristics determined from experimentations on a Kolsky pressure bar type apparatus, these investigators were able to estimate the value of K_{Ic} for loading rates near 10^6 MPa $\sqrt{m}$ s^{-1}.

Generally, the machine testing techniques were limited to maximum loading rates of about 10^5 MPa $\sqrt{m}$ s^{-1}. Recently, a new experimental method has been developed by Costin, Duffy and Freund (1976), and Costin (1978). This technique is an

adaptation of the Kolsky pressure bar and consists of a long bar of 1 in. diameter, with a prefatigued circumferential notch, which is loaded to failure by a rapidly rising tensile pulse resulting from the detonation of an explosive charge. The loading rates so reached are of about 10^6 - 10^7 MPa $\sqrt{m}$ s^{-1}.
The purpose of this paper is to present an experimental procedure derived from Costin's technique, which permits the determination of the dynamic fracture initiation properties of metals at very high loading rates, in excess of 10^7 MPa $\sqrt{m}$ s^{-1}.

EXPERIMENTAL APPARATUS

The apparatus is an adaptation of a dynamic tensile machine familiarily named "Cross-bow" which has been modified to allow fast tensile loading of a fatigue-cracked specimen.

Specimen

The specimen consists of a solid round bar, 20 mm in diameter and 1 m in length (Fig.1). A notch is machined into the bar at 0.66 m from the loading end, and so that the faces are parallel and the root has a sharp tip to facilitate the initiation of a fatigue crack.

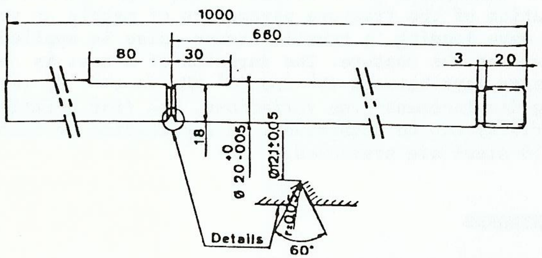

Fig.1. - Notched specimen.

A circumferentially uniform fatigue crack is grown from the root of the notch leaving an unfractured ligament of about 9 mm of diameter. The fatiguing is accomplished by means of rotating beam described below.
On either side of the notch small flat areas are machined to accomodate the optical measuring device which will be presented later.
At one end of the bar, a bulky metallic piece is screwed which will be used as a moving head and will be hit by a projectile.
Strain gages are attached to the specimen to measure the portion of the loading pulse transmitted through the notched region : the magnitude of that transmitted pulse is directly proportional to the average net section stress at the fracture site. The location of gages is close enough to the crack to avoid the dispersion of the pulse and far enough to ensure that measurements at the surface accurately reflect the character of the transmitted pulse.

The Fatigue Apparatus

On account of large sizes of the specimens, these are often slightly curved so that the fatiguing sets a problem because it becomes difficult to obtain constant momentum.

Thus, we have been constrained to realize a special machine, the diagram of which is schematically shown Fig.2.

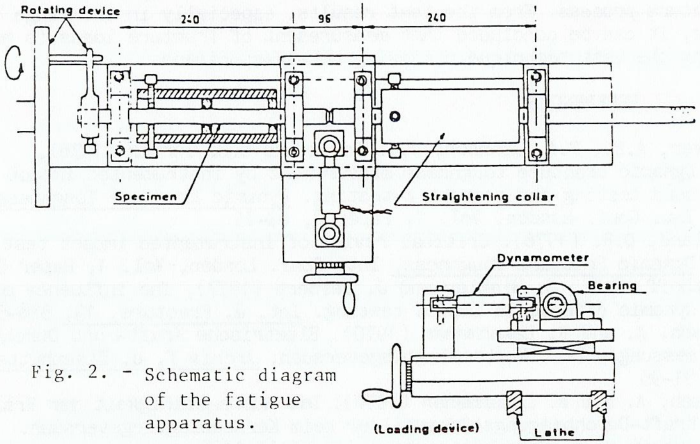

Fig. 2. - Schematic diagram of the fatigue apparatus.

In this apparatus the specimen is supported by four bearings. Two bearings are fixed to the stand of the machine (a lathe), the two others are positioned on the tool-slide and can move with it. The specimen is loaded transversaly and acts as a supported beam with equal loads applied to either side of the notch. By rotating the specimen, each point of the notch root is loaded alternately in tension and compression.
The applied load is determined by the displacement of the tool-slide and is measured by means of a short dynamometer.
Since the bars have a slight permanent curvature, resulting from fabrication process, two straightening collars are placed on the specimen, between the support bearing and the load bearing. Several sets of screws allow to bend and to straighten the bar, outside the notched region so that the specimen is loaded with a constant momentum.
After the specimen is adjusted properly, the required initial load is applied and the bar is rotated at approximately 130 r.p.m.
As the crack grows, the load does not remain constant throughout the fatiguing process. Since the load is continuously recorded, the amount of load relaxation is used as a measure of the growth of the crack.
An example of a pre-cracked specimen is shown Fig.3. It can be seen that the fatigued zone is uniform, and that the axis of the bar and of this zone are concentric.

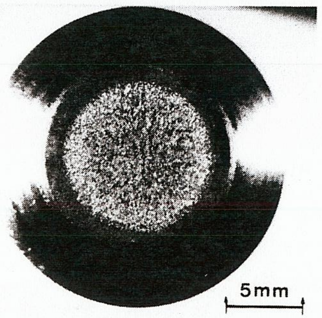

Fig.3. - Annular fatigue crack of a pre-notched specimen.

Testing Apparatus

A schematic diagram of the apparatus is shown in Fig.4.

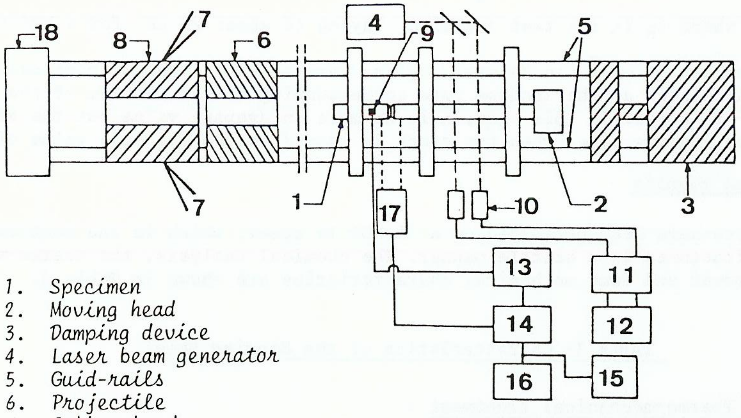

Fig.4. - Schematic diagram of the dynamic fracture apparatus.

1. *Specimen*
2. *Moving head*
3. *Damping device*
4. *Laser beam generator*
5. *Guid-rails*
6. *Projectile*
7. *Rubber-bands*
8. *Propeller*
9. *Gages*
10. *Photo-electric cells*
11. *Trigger unit*
12. *Electronic Counter*
13. *Amplificators*
14. *Biomation : waveform recorder*
15. *Display monitor*
16. *X-Y recorder*
17. *Optical extensometer*
18. *Winch*

This apparatus consists of two parallel guide-rails between which moves a projectile propelled by rubber bands. The projectile impact speed ranges from 3 to 40 m s^{-1}. The specimen, positioned between the rails, is supported by three bearings. At one end of the specimen is fixed a moving head which is hit by the projectile producing a tensile stress wave along the bar. After the rupture of the bar the projectile and the fractured part of the specimen are stopped by an hydraulic damping device.

Load measurement. As indicated previously, the measurement of the load and its evolution against the time is obtained by means of gages sticked on the specimen. An example of load-time record is shown in Fig.5.

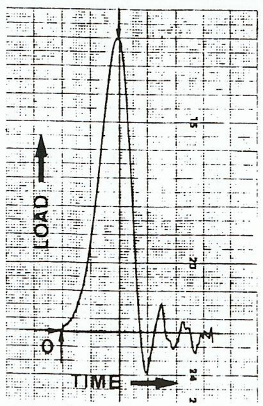

Fig.5. - Variation of load against time. (1085 N/div, 1 µs/div).

Measurement of crack-opening displacement. Two methods have been tried for the measurement of crack-opening displacement.
The first is the technique worked out by Costin, Duffy and Freund (1976) who use an optical device based on the phenomenon of Moiré fringes. The device employs matched set of guids that are produced photographically and fixed to the specimen on each side of the notch as shown in Fig.6. Any relative displacement between the two guids produces a displacement of the Moiré fringes, and a photodiode records the resultant oscillations in the light intensity. From the number of light-dark cycles recorded, it is possible to know the displacement between the outer edges of the notch and so, to obtain the crack-opening displacement against the time.

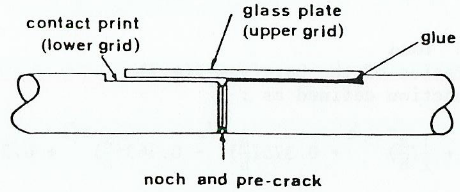

Fig. 6. - Experimental device for the measurement of displacement by Moiré fringes.

This method, which is successfully employed by Costin and colleagues on a split Hopkinson bar, seems nevertheless to be inadequate in the case of our apparatus, because the passage of the projectile produces parasitic reflexions which make the output signal difficult to analyse.
For this reason, a second technique has been used which employs an electro optical extensometer. This extensometer converts the distance between two targets of the specimen into an analog voltage, without contact to the specimen. The large frequency response (flat from 0 to 200 kHz, - 3 dB from 0 to 400 kHz) and the very short rise time (1 µs from 0 to 63 % of the full scale) allow a good accuracy of the dynamic results. Special lens units are mounted for adaptation to different gage lengths : the optical device used for fracture tests permits a displacement range of 1 mm (corresponding to a 10 V output signal) and a gage length laying between 5 and 25 mm.
With this technique, the crack-opening displacement is directly obtained as a function of time : an example of record is shown in Fig.7.

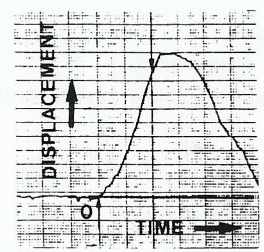

Fig. 7. - Variation of the crack opening displacement against the time (3.3×10^{-3} mm/div, 1 µs/div)

From the load-time curve and displacement-time curve, the load-displacement curve can be directly determined.

ANALYSIS OF DATA

Calculation of Fracture Parameters

Having determined the load-displacement curve for a test, the various fracture parameters can be calculated. For a brittle material, the parameter of interest is K_{Ic}, the plane strain fracture thoughness. K_{Ic} is calculated according to Tada, Paris and Irwin (1973) as :

$$K_I = \frac{P}{b^{3/2}} Y$$

where :

P = applied load
b = outer radius of the bar (see Fig.7)
Y = size function defined as :

$$Y = \frac{\sqrt{1 - a/b}}{2\sqrt{\Pi}} \left[\left(\frac{a}{b}\right)^{-3/2} + \frac{1}{2}\left(\frac{a}{b}\right)^{-1/2} + 0.375\left(\frac{a}{b}\right)^{1/2} - 0.363\left(\frac{a}{b}\right)^{3/2} + 0.731\left(\frac{a}{b}\right)^{5/2} \right]$$

where :

a = ligament radius (see Fig.8).

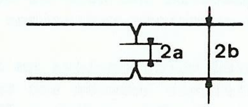

Fig. 8. - Designation of geomatrical parameters.

The load P used in calculating K_{Ic} is determined from the load-displacement curve in accordance with ASTM standards by using the 5 % slope offset procedure.
When testing more ductile materials, the specimen size is insufficient to contain the plastic zone and no valid K_{Ic} can be calculated. For this purpose, Rice's J-integral is used, written as :

$$J = \int_0^P \left(\frac{\partial \delta}{\partial l} \right)_P dP$$

where :

l = crack length
δ = load-point displacement

For a notched rod bar specimen, Rice, Paris and Merkle (1973) have shown that this expression for J becomes :

$$J = \frac{1}{2\Pi R^2} \left[3 \int_0^\delta P \, d\delta - P\delta \right]$$

where P is the applied load and R the radius of the specimen. In fact, the measured displacement is composed of two parts as :

$$\delta_{TOT} = \delta_{nc} + \delta_c$$

δ_{nc} being the elastic displacement that would occur if no crack were present, δ_c being due to the presence of the crack. However, for the studied range of loading, it can be supposed that $\delta_{nc} \ll \delta_c$, so that $\delta_{tot} \simeq \delta_c$. Thus, J can be evaluated directly as a function of displacement from the load-displacement record.
The last parameter of interest is $\mathring{K}$, which can be refined as :

$$\mathring{K} = \frac{K_{Ic}}{t_R}$$

where t_R is the test duration, laying to about 20 µs for a brittle material.
An other definition of $\mathring{K}$ can be used, which seems to have a better physical mean : K can be calculated as the loading rate corresponding to the maximum of the slope of the (P - t) curve. In this case, $\mathring{K}$ is no more an average value but the effective value of the loading rate, when the crack is loaded to the critical value of K_{Ic}.

Experimental Results

Dynamic tests have been performed on a 35 NCD 16 steel, which in the heat-treated condition fractures in a brittle manner. The chemical analysis, the thermo-mechanical treatment and some mechanical characteristics are shown in Table 1.

TABLE 1- Characteristics of the Studied Steel.

Thermo-mechanical treatment :

water-quenching from 875°C
+ 2 hours at - 80°C
+ 4 hours at 210°C

Analysis :

C	Mo	Si	Mn	S	P	Ni	Cr
0,358	0,27	0,33	0,36	0,005	0,011	3,70	1,75

Characteristics :

Ultimate tensile stress = 1870 MPa   hardness = 51,5 HR
0.2 % yield stress = 1530 MPa   rupture strain = 9 %

A summary of the experimental results is presented in Table 2 and a comparison is made between dynamic and static values.

TABLE 2 - Experimental Results on 35 NCD 16 Steel.

a/b	P N	K_{Ic} MPa $\sqrt{m}$	$\mathring{K}$ MPa $\sqrt{m}$ s^{-1}	t_R µs
0.423	112300	111.5	10^7	19
0.438	118000	111	8.5×10^6	21
0.442	113950	106	1.5×10^7	19
0.437	120460	113.6	1.7×10^7	18
0.448	118840	108	7.5×10^6	27
0.450	111150	109	1.9×10^7	20
0.472	112136	93	2.6×10^6	46
	stat.	87		

It can be seen that K_{Ic} increases with $\mathring{K}$, from 87 MPa $\sqrt{m}$ in quasi static conditions to about 110 MPa $\sqrt{m}$ at loading rate of 10^7 MPa $\sqrt{m}$. s^{-1} . Since there are few results in dynamic fracture, the comparison with other works is difficult. However, this evolution of K_{Ic} with $\mathring{K}$ seems to be in good agreement with results obtained by Wilson, Hawlay and Duffy (1979) on a 1810 cold rolled steel, by Pluvinage (1980),

and with the calculation of Krafft(1964). Krafft has shown that the value of K_{Ic} decreases with increasing loading rates of 10^3 and 10^6 MPa $\sqrt{m}.s^{-1}$, and then increases rapidly in the region of high loading rates, nominally 10^6 - 10^8 MPa$\sqrt{m}.s^{-1}$. Of course, this evolution depends on temperature and material. Furthermore, the strain rate sensitivity of the material is an important parameter which can influence the variation of K_{Ic} with $\dot{K}$. So, in this type of dynamic study, it seems to be necessary to know the mechanical behaviour of the material at high strain-rates, by experimental tests performed, for example, on a split Hopkinson pressure bar.
These results on a 35 NCD 16 steel are the first we have obtained with our apparatus. They have been performed essentially to test the technique and the measurement devices. For this reason, the study is not yet finished, and work is in progress on this steel and on an other, 10 CD9 10 steel, which fractures in a ductile manner.

CONCLUSION

A new experimental technique has been described. This technique is designed to determine the usual fracture parameters under extremely high loading rates, upper than 10^7 MPa$\sqrt{m}.s^{-1}$. Data from this dynamic fracture apparatus, when compared to quasi-static data, provide a direct method of determining the sensitivity of fracture thoughness to loading rate.
Some experimental results on a 35 NCD 16 steel have been presented, and work is in progress to obtain more data on the dynamic fracture of materials, which only begins to be studied.

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REFERENCES

Krafft, J.M. (1964). Correlation of plane strain crack toughness with strain hardening characteristics of a low, a medium and a high strength steel, Applied Materials Research , April, 88-101.
Eftis, J., and J.M. Krafft (1965). Transactions American Society of Mechanical Engineers, Journal of Basic Engineering, March, 257-263.
Rice, J.R., P.C. Paris, and J.G. Merkle (1973). Some further results of J.integral analysis and estimates, ASTM STP 536, 231-245.
Tada, H., P.C. Paris, and G.R. Irwin (1973). The stress analysis of cracks handbook, Del Research Corporation, Hellertown, Pennsylvania.
Costin, L.S., J. Duffy, and L.B. Freund (1976). Fracture initiation in metals under stress wave loading conditions. Brown University Technical Report NSF ENG 75 - 09612/1.
Costin, L.S. (1978). The effect of loading rate and temperature of the initiation of fracture in a wild, rate-sensitive steel. Brown University Technical Report NSF ENG 77 - 07798/2.
Wilson, M.L., R.H. Hawley, and J. Duffy (1979). The effect of loading rate and temperature on fracture initiation in 1020 hot-rolled steel. Brown University Technical Report NSF ENG 77 - 07798/3 and N 00014 - 78 - C - 0051/3.
Pluvinage, G. (1980). Private communication.