

Temperature variations around the crack tip during a fracture test

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Abstract

Preliminary results are reported of the temperature variations in a fatigue pre-cracked compact tension specimen of AISI 316, subjected to a uniformly increasing cross-head displacement. The temperature variations in the regions surrounding the crack tip are sensed by three point-like thermistors.

At the thermoelastic-plastic instability the load vs. time characteristic exhibits a barely perceptible kink. Conversely, the initial thermoelastic cooling is followed by a sudden temperature rise near the crack tip and a delayed, smoother rise at greater distances. This experimental procedure, based on "thermal emission" allows one to identify with precision the formation and development of the plastic zone.

Riassunto

Variazioni di temperatura in prossimità dell'apice della cricca, durante una prova di frattura

Sono presentate misure preliminari delle variazioni di temperatura in un provino « compact tension » di AISI 316, preintagliato a fatica, caricato con velocità di traversa costante. Le variazioni di temperatura nelle regioni adiacenti all'apice della cricca sono misurate utilizzando tre termistori quasi puntiformi.

All'instabilità termoelastoplastica la caratteristica carico-tempo presenta una curvatura appena percettibile. L'iniziale raffreddamento termoelastico è invece seguito da un improvviso aumento di temperatura in prossimità dell'apice della cricca, e da un aumento ritardato e smorzato a distanze maggiori. Questa procedura sperimentale, basata sulla « emissione termica », permette di identificare con precisione la formazione e lo sviluppo della zona plastica.

Introduction

The objective of this contribution is to offer experimental evidence of the possibility of deducing relevant information on the fracture process from temperature variations measured at the sample surface during a fracture test.

Only little attention is being paid to temperature changes occurring in materials undergoing yielding^(1, 2, 3) or plastic deformation⁽⁴⁾ and fatigue or fracture.⁽⁵⁾ On

the other hand, it is common knowledge that the mechanical transformations are thermodynamic in nature: the majority of "mechanical" transformations are irreversible, only the thermoelastic one, governed by the Kelvin effect (1851), being in practice reversible. All "mechanical" transformations are obviously controlled by the first principle of thermodynamics. The intriguing importance of thermal energy in the overall energy balance can be expressed as follows:

"Although it is established that nine tenths of the work done in plastically deforming a metal at room temperature is at once converted into heat, little is known of the mechanism of this conversion" (F.R.N. Nabarro, 1967). Therefore, at temperatures high enough to allow for energy degradation via, e.g., the production and annihilation of large dislocation segments, only a minor part of the mechanical work is stored in the sample as potential energy. The major part of it is eventually dissipated in the thermal bath of the sample with entropy production.

In this context it might be challenging to investigate whether damage could be envisaged in terms of the stored energy of cold work. Should a close connection exist between the two, the local stability of a material sample could be related to an upper limit of the specific potential energy stored in it.⁽⁷⁾ In this perspective, we have decided to take advantage of previous

experimental knowledge accumulated on the use of temperature changes as indices of fundamental processes occurring in a material under stress.⁽⁸⁾ Two

basic results are briefly reported below:

a) in the practically reversible (thermo)elastic regime, elongation (i.e. volume expansion) under tensile loading drives the sample towards thermoelastic cooling. In the ideal case of an isoentropic and adiabatic deformation leading to a percentage volume change $\Delta V/V$, the percentage temperature drop $\Delta T/T$ is given by the Kelvin law

$$\Delta T/T = -\gamma (\Delta V/V).$$

Here γ is Gruneisen parameter and can be expressed in terms of the thermal expansion coefficient α , the isothermal modulus of compressibility K_T , and the specific heat per unit volume at constant volume C_v via the equation of state⁽⁹⁾

$$\gamma = \alpha K_T/C_v$$

b) in the fully irreversible (plastic) regime, the flow phenomena lead instead to energy dissipation, a positive heat source; deformation in the plastic regime leads to heating of the sample.

By implementing the available instrumentation as indicated in the following paragraph, tests were made to ascertain the significance and usefulness of temperature measurements during a fracture process.

Experimental set-up

Two tests were made on AISI 316 compact tension specimens; specimen dimensions appear in Fig. 1. The specimens were fatigue pre-cracked to a crack length

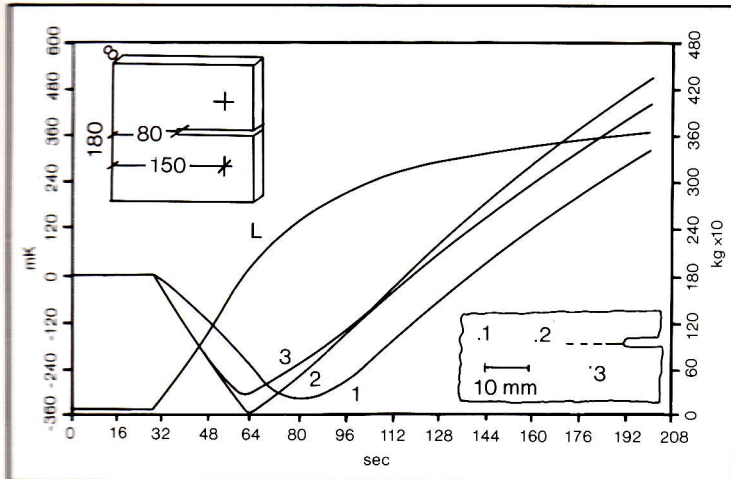


Fig. 1 - Load (L) and temperature (1, 2, 3) vs. time recordings at locations 1, 2 and 3 during Test 1. Specimen dimensions. Thermistor locations and initial and final crack extensions. Crosshead velocity: 0.2 cm/min.

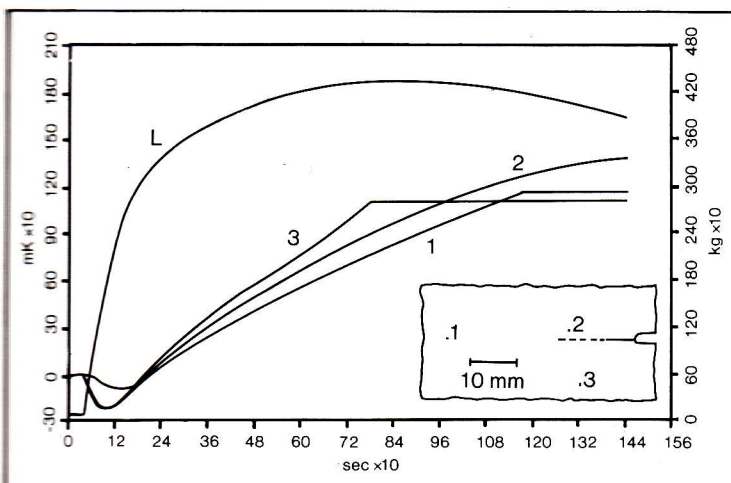


Fig. 2 - Load (L) and temperature (1, 2, 3) vs. time recordings at locations 1, 2 and 3 during Test 2. Thermistor locations and initial and final crack extensions. Crosshead velocity: 0.1 cm/min.

of a few millimetres. They were loaded by an Instron test machine, with constant crosshead velocity (0.1 or 0.2 cm/min). The temperature was sensed by three negative-temperature-coefficient thermistors, the dimensions of which did not exceed 0.2 mm. In the configuration used, these sensors, together with the dedicated circuitry, reach a resolution of the order of 2 mK, with a time constant of a few tenths of a second. Sensor positions are indicated in Figs. 1 and 2. Temperature and load signals were recorded by a PDP 11/03 microcomputer, equipped with analogue-to-digital conversion inputs.

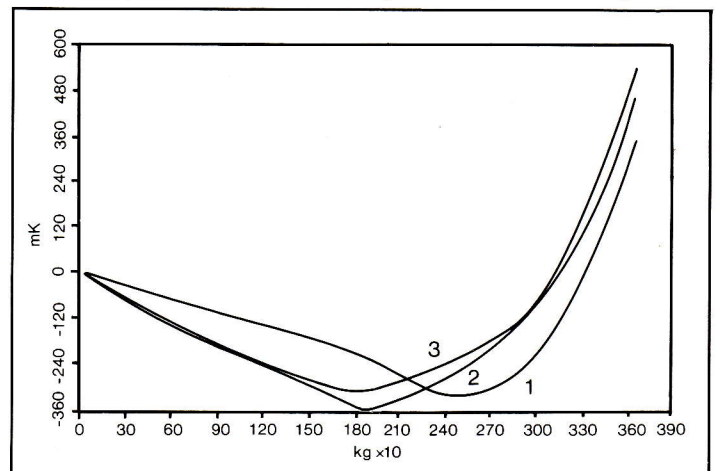
Experimental results

Temperature and load recordings are presented in Fig. 1 (first part of test 1) and in Fig. 2 (full duration of test 2). The initial cooling at the three sensor locations indicates that the deformation is completely elastic; Thermistors 2 and 3 cool down at a higher rate than Thermistor 1, which is located farther away from the crack tip, indicating, as expected, a higher deformation rate near the crack tip.

Thereafter three events happen simultaneously, as is more evident in Fig. 1: the temperature at Thermistors 2 and 3 begins to rise, the temperature at Thermistor 1 keeps falling, but at a faster rate, and the load increases at a slower rate. All these facts indicate the beginning of plastic flow near the crack tip: heat generated in the plastically flowing zone is detected by the neighbouring Thermistors 2 and 3; as a result of stress redistribution due to the beginning of plastic flow, the region around Thermistor 1 must bear a higher stress. Consequently, it is deformed at a higher rate, yet in the elastic regime, as indicated by the increase in its cooling rate; the lower overall specimen stiffness due to plastic flow is reflected by the lower rate of load increase. In Figs. 3 and 4 time has been eliminated, and temperature vs. increasing load is plotted. The temperature behaviour outlined before is even more evident in this representation.

The temperature vs. stress behaviour is however different in the two tests. More pronounced slope changes from the three thermistors occur in Sample 1 than in Sample 2. This different behaviour could be ascribed to differences in e.g. initial fatigue crack morphology and/or local microstructure. The generalized heating which is eventually reached indicates a spread of plastic flow over large portions of

Fig. 3 - Temperature (1, 2, 3) vs. load recordings at locations 1, 2 and 3 during Test 1.



the sample; the temperature behaviour in the phase following yield reflects both the growth of the plastically flowing zones, and the diffusion of heat from these zones to the surrounding ones.

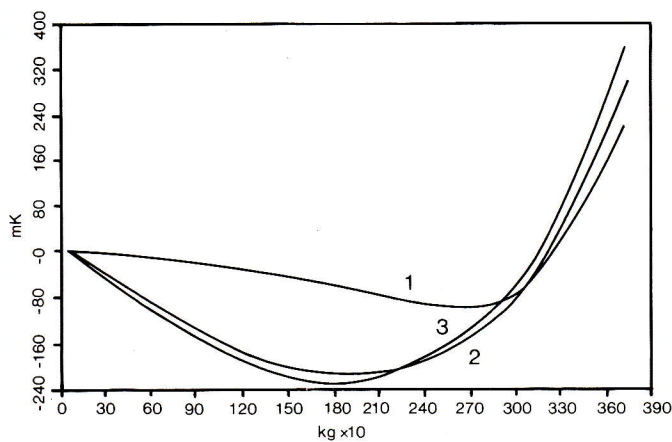


Fig. 4 - Temperature (1, 2, 3) vs. load recordings at locations 1, 2 and 3 during Test 2.

Conclusions

The tests performed indicate that the temperature variations which can be detected in a fracture test can provide significant additional information with respect to data obtained by other methods. In particular:

- the temperature variations during fracture tests are in the order of tenths of a degree; these variations, though apparently small, can be detected and resolved using thermistor transducers and adequate laboratory equipment;
- the detected temperature variations are strictly related to the local deformation rates and deformation mechanisms; i.e. temperature variations are related to the elastic volume deformation rate, as well as to the irreversible nature of the plastic deformation mechanisms; furthermore, to a difference with respect to strain gauges, the temperature transducers are not affected by an upper saturation level; point-like temperature sensors can be applied in a simple way, and allow a fine mesh measurement of local values. Nevertheless, temperature variations are related to deformation rates and only indirectly to deformation levels;
- temperature variations in the sample are affected by heat diffusion, which plays a significant role; as a result, at each point they are also affected by temperature variations and deformation phenomena in the

surrounding zones, being slower and retarded far from crack tip. A satisfactory deconvolution of diffusion effects necessarily requires a high number of measurement sites.

The results reported above are preliminary. Yet they clearly indicate the onset and development of the plastic regime at the crack tip and around it. Further work should be done in order to ascertain the actual possibility of pinpointing the initiation of crack propagation.

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