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EVALUATION OF FRACTURE INCUBATION TIME FROM QUASISTATIC TENSILE STRENGTH EXPERIMENT

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Abstract. Incubation time being the main characteristic parameter for dynamic fracture process is experimentally measured for PMMA utilizing optical methods. The specimen is quasistatically loaded in standard tensile testing machine until brittle fracture occurs when the sample is split into two parts. Normally this splitting of brittle materials is accompanied by the impact unloading of the sample. In considered tests tensioned samples were dynamically unloaded by stress drop wave, generated by fracture process and registered by photoelasticity technique at a certain distance from breaking line. The same experiment is simulated using ANSYS FEM software package and the incubation time is evaluated numerically. The simulation results are in a good coincidence with experimental measurements, proving the applicability of the proposed simple method for brittle fracture incubation time measurements.

1. Introduction

It is known and nowadays generally accepted (see ex. [1, 2]) that dynamic fracture caused by intensive transient loads (for example explosive of intense impact load) cannot be predicted on the basis of classical fracture mechanics. Numerous experimental results [3, 4] reveal contradictions with classic approaches (i.e. critical stress or critical stress intensity factor concepts) that can only be explained by inapplicability of static approaches in dynamic problems. In other words, transient processes including for example small-scale damage, precessing macroscopic fracture or medium inertia should be taken into account.

Spatial dimension being introduced into fracture criteria is providing a possibility for correct prediction of quasistatic fracture for problems with non square root stress singularities. This type of criteria was originally proposed by Neuber [5] and Novozhilov [6]:

$$\frac{1}{d}\int_{x^*-d}^{x^*}\sigma(x)dx \le \sigma_C. \quad (1)$$

Here σ_C is the material ultimate stress, $\sigma(x)$ stands for the stress in point x and x^* is the location of fracture. Size d can be received as $d = 2K_{IC}^2/\pi\sigma_C^2$, where K_{IC} is the critical stress intensity factor, from the requirement of coincidence of (1) with Irwin-Griffith critical stress intensity factor fracture criterion in the case of square-root singularity. This size may be treated as a characteristic size of a fracture process zone being a scale level identifier [7]. This is a minimal size for a damaged medium that can be called “fracture” at a chosen scale level (e.g. minimal length of a microcrack in a problem of crack propagation). Currently the criterion (1) is included as a special case into the incubation time fracture approach [7-10] introducing spatial-temporal discretization of fracture process. This criterion, along with the

Suppose we perform a classic tensile test on a standard flat sample. Quasi brittle fracture of the tested material is supposed. At some moment of time$t$ the sample is divided into two parts as the stress in the sample reaches critical value P. Following the classic concepts of linear elasticity fracture event should result in an instantaneous stress drop at a fracture point. This stress drop would generate a step shaped relaxation wave in the sample. The stress at the fracture point may be represented by $\sigma(t) = P - PH(t)$ with $H(t)$ being the Heaviside step function.

However for real processes such a suggestion contradicts the nature. It takes time for the fracture process to develop from micro scale to macro scale,material needs time in order to accelerate and start moving. In other words, failure should not be represented as an instantaneous event, as it is a continuous process in time. According to this natural assumption stress as a function of time in the break point can be presented as: $\sigma(t) = P - Pf(t)$, where $f(t)$ is some function without vertical slope (Fig. 1) continuously growing from 0 to 1.

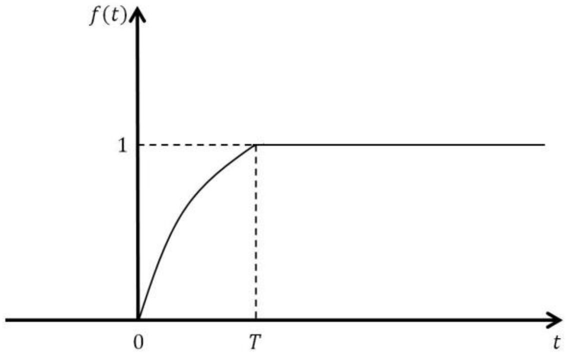

Fig. 1. Possible form of function $f(t)$.

Function $f(t)$ may be treated as a “damage accumulation” function with $f(0) = 0$ corresponding to undamaged material and $f(T) = 1$ associated with observed macroscopic fracture. The use of such function makes it possible to take into account relaxation processes at micro scale level preceding macroscopic fracture, e.g. appearance, development and coalescence of micro cracks.

Turning back to classic approach implying that stresses are relaxed instantly and follow the law $\sigma(t) = P - PH(t)$, with $P = \sigma_c$ being the ultimate stress, time to fracture t^* can be easily calculated substituting stress time dependency into fracture criterion (2) and is found to be equal to the incubation time τ. Having in mind the damage accumulation concept one can conclude that the time of stress drop T from the function $f(t)$ should be regarded as time to fracture t^* and, hence $T = t^* = \tau$. This fact gives a theoretical background for an experimental technique that can be used in order to measure the incubation time. In these experiments time history of the stress drop in the relaxation wave traveling through the sample being initiated by fracturecaused by quasistatic tensile loading should be measured. Measured time of stress relaxation should give the brittle fracture incubation time for the tested material.

The proposed experimental method involves photoelasticity methods to study the stress state of the sample. The tested PMMA is photoelastic material possessing marked birefringence properties. This means that a ray of light passing through PMMA receives two refractive indices along two principal stress directions in the stressed sample. Due to the difference between the refractive indices relative phase retardation appears between two components and hence two electromagnetic waves are produced. Optical interference of the two waves generates the fringe pattern that can be easily registered. One may establish direct

"fast" and "slow" time scales are presented. From graph 3 b) it is clear that 17 μs are needed for stress to decrease to zero, while graph a) depicts quasistatic growth of tensile stress. On both of the graphs 3 fringes passed the point where the laser beam was pointed.

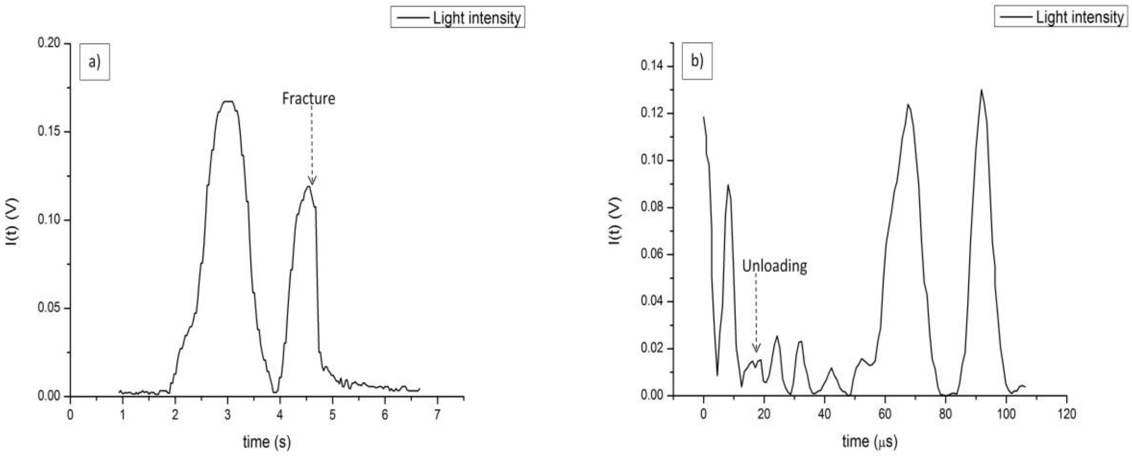

Fig. 2. "Slow" (a) and "fast" (b) time scale dependencies *Light intensity vs. time.*

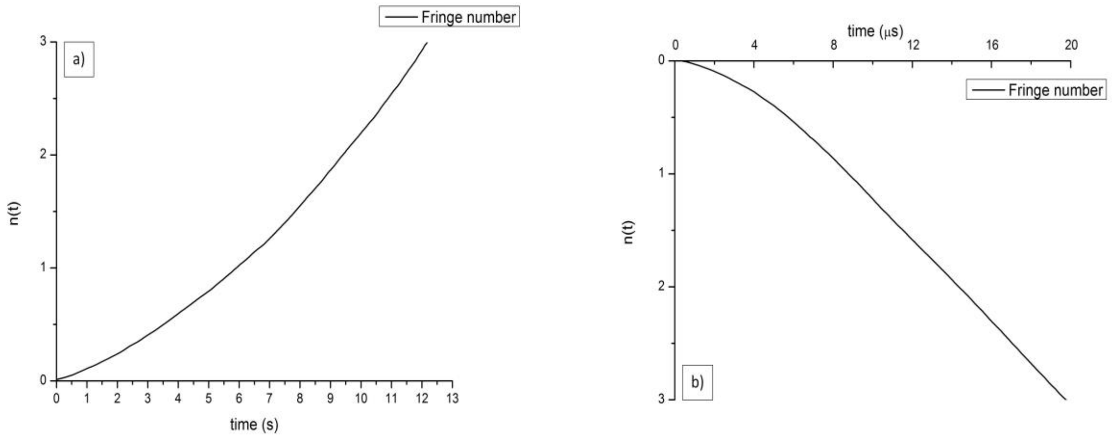

Fig. 3. "Slow" (a) and "fast" (b) time scale dependencies. *Fringe number vs. time.*

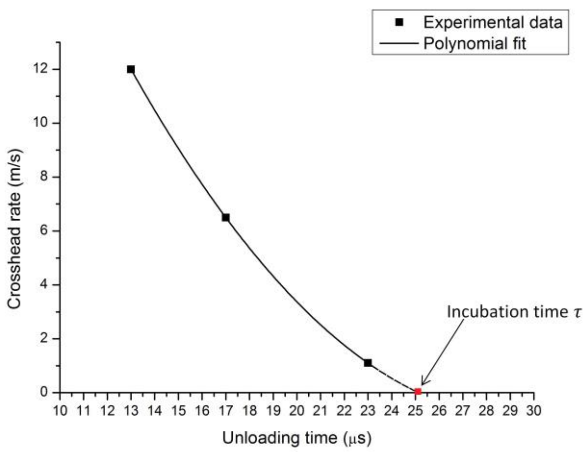

Fig. 4. *Crosshead rate vs. unloading time* dependency. Experimental points fit by 2[nd] order polynomial. Intersection with abscise corresponds to the incubation time.

$U_y(X \in \Gamma_1, t) = vt,$

$U_y(X \in \Gamma_2, t) = 0$ – symmetry condition

$\sigma_y(X \in \Gamma_3, t) = \sigma_{xy}(X \in \Gamma_2 \cup \Gamma_3, t) = 0.$

Here $X = (x_1, x_2) = (x, y)$ is the coordinate, $\overline{U} = (U_1, U_2) = (U_x, U_y)$ gives the displacement vector and v is the testing machine crosshead rate. See Fig. 5 for details.

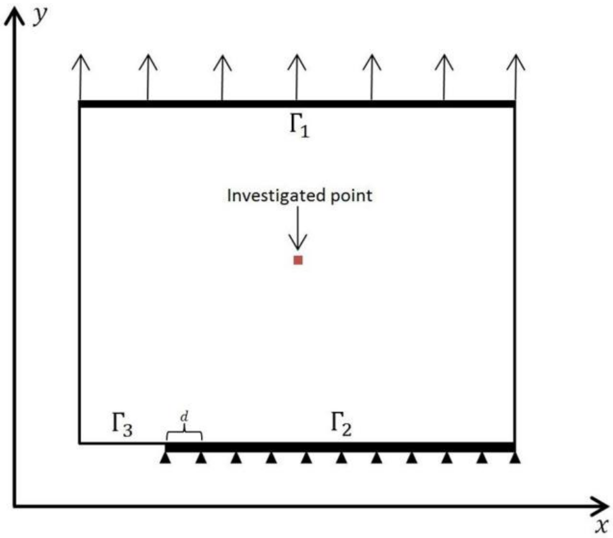

Fig. 5. Simulation scheme.

Figure 6 shows stress history in a point in the middle of the sample corresponding to the point where the stress was measured by photoelastic method. Time between the moments when the unloading wave arrives to the measurement point and when the stress is completely relaxed can be estimated from Fig. 7. It was found to be equal to $25\,\mu s$ for very small crosshead movement speeds.

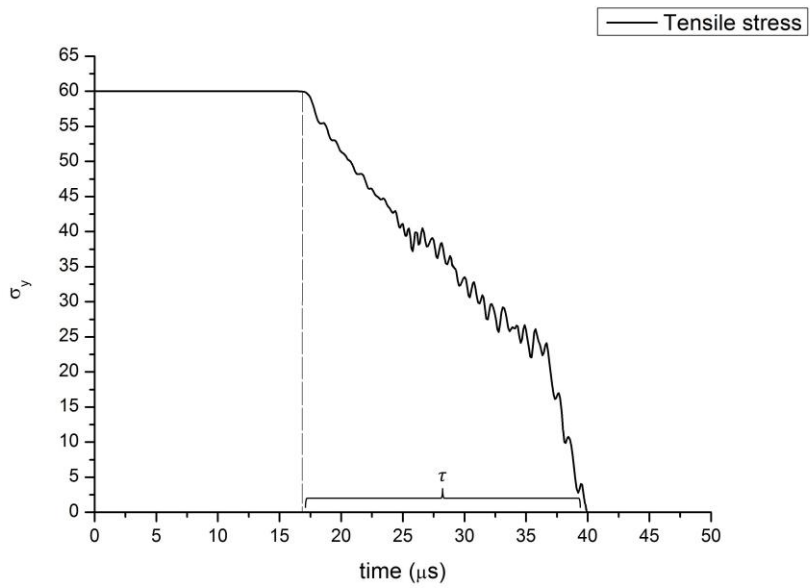

Fig. 6. Tensile stress history in the investigated point.

4. Conclusions

Incubation time is a key parameter for prediction of transient processes [13] (for example brittle fracture). In this paper a relatively simple method for incubation time of brittle fracture measurement in transparent materials with birefringence properties is proposed. The method is based on quasistatic tensile loading of a sample followed by brittle fracture. The incubation time is measured as time needed for relaxation of tensile stress at a point distant from the fracture interface. This experimental approach gives value of brittle fracture incubation time around 25 μs for thick PMMA specimens. The same result may be obtained using finite element method simulation. To simulate dynamic processes preceding macro scale fracture (in our case crack propagation) smaller scale incubation time evaluated in the case of spall fracture problem (i.e. [19]) can be utilized. This result once again [20] testifies a possibility to establish interconnection between fracture parameters on different scale levels The incubation time measured with the proposed method is very close to with the value obtained in complex and expensive purely dynamic tests (30 μs). A small discrepancy in the results of the two experimental approaches should be the topic for future investigation. One of the possible explanations can consist in considerable variation of PMMA material properties. The proposed rather simple and cheap technique can be used in order to measure incubation time of fracture in brittle transparent materials with birefringence properties. The technique can be extended to measure incubation time for brittle reflective materials or arbitrary brittle materials with thin reflective layer attached to the surface.

Acknowledgments

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