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EXPERIMENTAL PART OF THERMODYNAMICAL FRACTURE MECHANICS PROGRAMME

Zemánková J., Jaroš P., Vavřík D.

Abstract. Thermodynamical fracture mechanics addresses the experimentators the requirements of measurement and identification of a new quantities, namely this ones connecting with the dissipation of energy in the structures. The paper describes methods of the plastic work identification .

1. Introduction

Actual absence of a functional and general fracture theory at the end of the 20th century, at the time of construction and operation of ever more sofisticated structures the failure of which could have immense consequences, results in an ever more intensive endeavour to formulate such theory. Existing approaches of one-parametric fracture mechanics (FM) are being revised and extended, e.g. in the form of two-parametric FM, simultaneously new concepts on a more general, physical basis are being sought. One of them is e.g. the thermodynamical FM, developed in the Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic in the framework of the grant project No. 106/95/1433 of the Grant Agency of the Czech Republic. All new approaches have in common an endeavour to formulate more accurate description of the processes and circumstances accompanying fracture in real structural materials with particular reference to the definition of the influence of lesser or greater plastic deformation of different intensity.

However, the two-parametric FM [1], although it still considers the limit value of the opening normal stress component (Mode I) as the principal cause of defect instability, derives it from the non-linear stress field. Thermodynamical FM, using the balance of the rates of the energy changes entering the process of damaging, is based on the decisive influence of the dissipated energy rate in the system. The primary source of dissipation in metal structures consists in plastic work. The consequence of these facts for experimental methods used in the study of fracture is the necessity of major concentration on the monitoring of the quantities directly correlated with plasticization or those which are indispensable as inputs to the accompanying numerical computations of elasto/plastic character. This is manifested elementarily in the description of a uniaxial tension test which should yield not only the characteristic linear load-displacement part of curves (E, υ, $R_{0.2}$), but also a description of constants of the Ramberg-Osgood relation, for example. This seems to be a considerable problem for our testing laboratories, incl. the authorized ones.

Thermodynamical FM addresses the experimentators directly the requirement of identification and quantification of irreversibly deformed parts of the body. In its framework the defect instability is considered as one of the state changes and transitions of the system in the course of its evolutionary trend governed by the principle of maximum energy dissipation rate (principle of maximum entropy production) [2]. Although the energy dissipation rate, as one of the balanced components, will be computed numerically, it is necessary to confront the computation results continuously with the reality of mechanical quantities ascertained experimentally. Numerical plasticity, even for two-dimensional problems, is based on a number of approximative assumptions and models the corrections of which are necessary to make the results creditable.

2. Specimens and its loading

In the framework of the above mentioned grant project an experiment was made using specimens made of two types of aluminum alloy (CSN 42 4201.1 and CSN 42 4203.6). All specimens were provided with artificial sharp stress concentrators made by a combination of water cutting and sparking out methods. Their lengths and locations were so selected as to provide plasticization of different scope at the defect front. For its quantification the theory of constraint factor through T-stress was used [3] The selection of specimen geometry and loading method were influenced also by the endeavour to compare the fracture stress prediction capacity of the individual FM approaches incl. the Sih' s S-criterion and our thermodynamical FM. For this reason they were derived from some solutions found in literature [4], applicable to selected materials. The specimens, marked as CC, CC_n and S (Fig.1), were loaded by regular tension until failure at a constant displacement of the loading machine grips. The experiment was performed with the assistance of the firm TECHLAB in the Institute of Thermomechanics AS CR (TIRA 2300 loading machine) and the Klokner Institute, Technical University, Prague (INSTRON TT-KM, extend to 250 kN and MTS 810, extend to 400 kN). In all cases, the destruction of the experimental specimens by the tension has been done with the constant displacement of the grips.

3. Measured variables and applied experimental techniques

To reach the thorough description of stress-strain process for later analyses the following experimental methods and equipment were used:

a) Modified method of grid consisting of periodically situated points created the circles with specific size of the diameter 0,6 mm or 1,2 mm in both orthogonal and vertical directions. Creation of the grids on analysed surfaces was done by photoresist technique. Visualisation of surface deformation and crack growth observation were realised through CCD camera Panasonic WV-BP310 and recording of the whole time process was enabled by SVHS videorecorder Panasonic AG7355. These results are presented in the separate paper [5].

b) Time records of the following variables were carried out by means of on-line multi-parametric computer system (in co-operation with TECHLAB, Ltd.):

- measurement by special potentiometric method with stabilised alternating current excitation (125 Hz), position of both exciting and signal electrodes is marked on Fig.1,
- surface strain near vicinity of the stress concentrator (Fig.1) was measured by miniature strain gauges with grid length 1,6 mm and width 1,2 mm.

Electric signals of all mentioned devices were conditioned for measuring card CSA 1208 with 8-cannels analog input and 12-bit A-D conventer inserted in notebook CardStar 100S and working under program INMES for measurement and data processing.

Time signals x-t measured with 2 resp. 5 Hz sampling frequency were transformed to desired x-y form utilising program MATLAB. Regarding to the conventional tensile diagrams the average longitudal displacement expressed as

$$\Delta l = \frac{1}{2}(u_1 + u_2),$$

where u_1 and u_2 are the edge displacements from extensometers, was chosen as the independent parameter (i.e coordinate x).

All the measured variables (force, potentional change, strain and COD at S-type specimens) can be graphically related to this parameter. The example of such result is presented in Fig.2 (specimen 2CC1b).

4. Summary of the experimental pieces of knowledge and conclusions

The description of test results as well as the preliminary evaluation of the experiment in the meaning of predictibility comparisons of different FM theories were presented in the paper [6] at the Engineering Mechanics 97 conference. Therefore, we shall only sum-up briefly as follows:

The confrontation of experimental results with theoretical predictions could be made only for the dural-aluminum alloy, as in the softer material the defect growth was differentiated markedly also across the specimen thickness (the condition of self-similar growth had not been maintaned).

In the comparisons of the nominal predicted fracture stress the one-parametric K_J approach in the framework of linear FM yielded best agreement for type S specimens, and worst agreement for type CC specimens (as many as 100% difference in the meaning of non-conservative prediction). For CC and CC_n specimens the Sih's S-criterion [4], according to the results of the numerical experiment predicted a several milimetres zone of stable crack propagation and curvature near the end specimen . None of these phenomena were observed physically during the experiment. However, the computed values of nominal fracture stresses following the phase of stable propagation differed in the numerical S-model from the measured values of these stresses at the moment of observed fast instability only by 11% (specimen CC_n) and by about -6% (specimen CC). A comparison with the predictions based on two-parametric FM could not be made for two reasons: on the one hand because this approach is applicable only to the cleavage mode of failure (in our test the SEM has confirmed its ductile type), on the other hand because the J-T and or J-Q toughness locus was not available for the materials used.

Our thermodynamical analysis was made in the first approximation only for the type CC specimens. It succeeded in determining the attained maximum force in the loading diagram for specimen of the given configuration and size with an accuracy of some 5%. The analysis has helped us to understand the relations of the loading curve history and the plastic deformation growth in the specimen. It also has explained why such high velocity of crack propagation was observed in these specimens and why the phase of stable growth was missing. It has shown, on the one hand, the possibility of a considerable generality of the model, on the other hand the need of combining it with micromechanical approaches which could enable the identification of not only plastic instability, but also fracture instability.

The simultaneous application of a few experimental methods enables to characterise their efficiency for the aim of the work, i.e. testing of the new fracture mechanics theory for bodies from materials with extensive energy dissipation under uniformly increasing loading.

1) The grid method offers an excellent survey of surface deformation of all area covered with the grid. It is very useful also for the stages of plastic deformation before the beginning of crack growth. Because the rate of energy dissipation was substantional parameter in this work, the full-field analysis of the shapes and sizes of plastic zones is very useful for correlating of the mathematical model. A new contribution was the application of the modern videosystem enabling both on-line observation of the crack and plastic zones growth in enlarged detail and permanent video-record for later analyses, esp. correlation of various

values and comparison of experimental with theoretical results including the criterion of crack instability.

2) Advanced handy and precise electric extensometers placed in proposed points of the specimen present true and easily checked value of real average strain in comparison to usually completely false reading from the movement of a testing machine mechanism which is influenced by creep and displacement in clamping grips, deformation of a frame etc. Especially for specimen of "S" type the used extensometer positioning is very important for evaluation of the loading unsymetry which is again extremely influenced by clamping grips design an by rigidity of the whole frame. The experimental results can be used for giving precision to the boundary conditions of numerical solution the results of which will become more faithful.

3) Despite of the fact, that used type of strain gauges was not ideal for the purpose, the gained relations show possibilities of this method for determination of the non-linearity beginning in the local versus average strain diagram. It can serve as a proof of plastification at defect tip area. This knowledge can be used for precisation of the numerical model again.

4) Proposed application of the potentiometric method as an indicator of the stable to unstable crack transition can easily lead to misinterpretation. There were found some significant changes of potential before unstable crack growth despite of the fact that no slow crack growth was confirmed by the fractography. The explanation can be found in principle discrepancy of the method which cannot separate between reasons of electrical resistance changes. They can be both of material origin (decreasing of specific conductivity due to tensile elastic and general plastic deformations) and of geometric changes of the body's shape (arise and growth of new free surfaces as slip lips and microcracks). Despite of these facts the method is the only one that can indicate even sub-surface changes. They are for description of the crack mechanics so significant that future effort for improvement of the method possibilities should be useful. The care will be taken to application of some new principles of measuring techniques (synchronous detection, shaping of waveforms, variable frequency etc.) directed to the improvement of distinguishing ability between surface and internal layers of electrical paths through the specimen based on the skinefect.

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Jaroslava Zemánková, Ing., CSc, ÚTAM AV ČR, Prosecká 76, 190 00 Praha 9, tel. 882334/206, Fax 884634, e-mail : ZEMANKOVA@ ITAM.CAS.CZ

Petr Jaroš, Ing., CSc, TECHLAB,s.r.o., Sokolovská 207, 190 00 Praha 9, tel/fax 6846434

Daniel Vavřík, Ing., Ing. ÚTAM AV ČR, Prosecká 76, 190 00 Praha 9

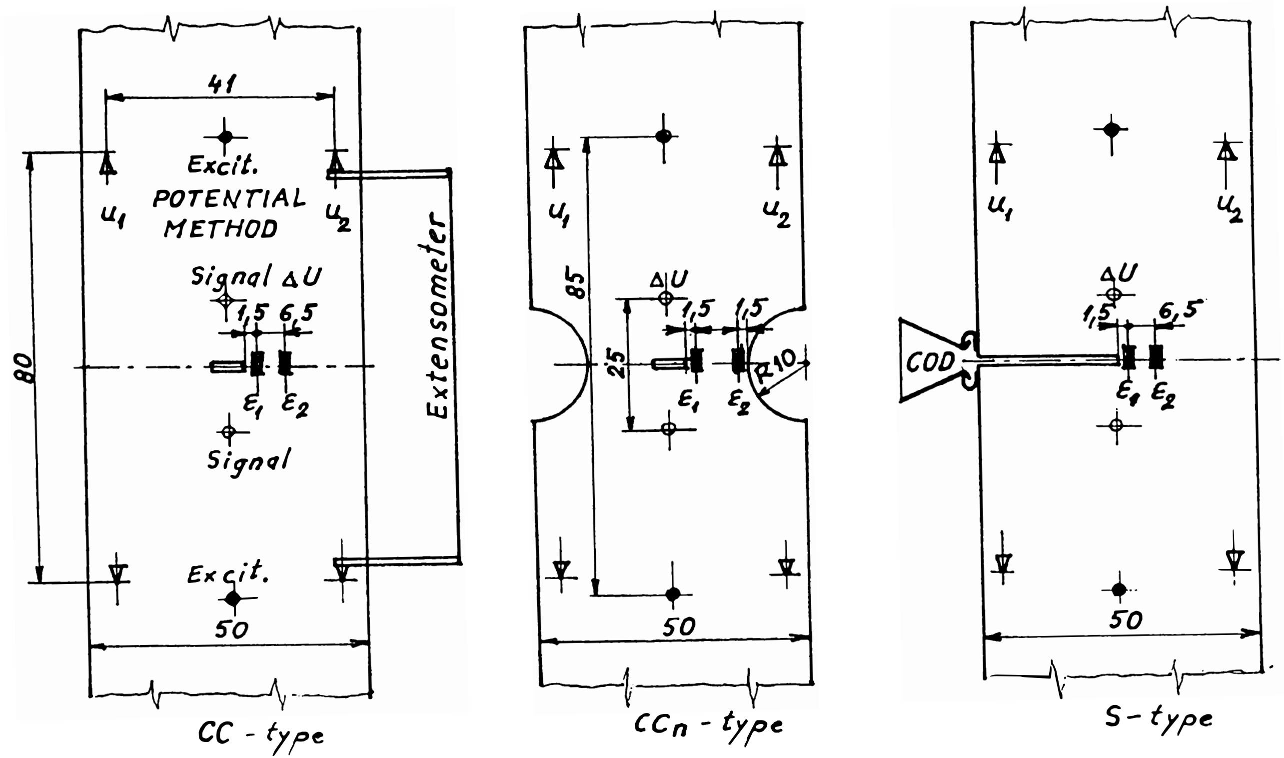

Fig. 1. The scheme of specimen types, dimensions and measuring gauges positions

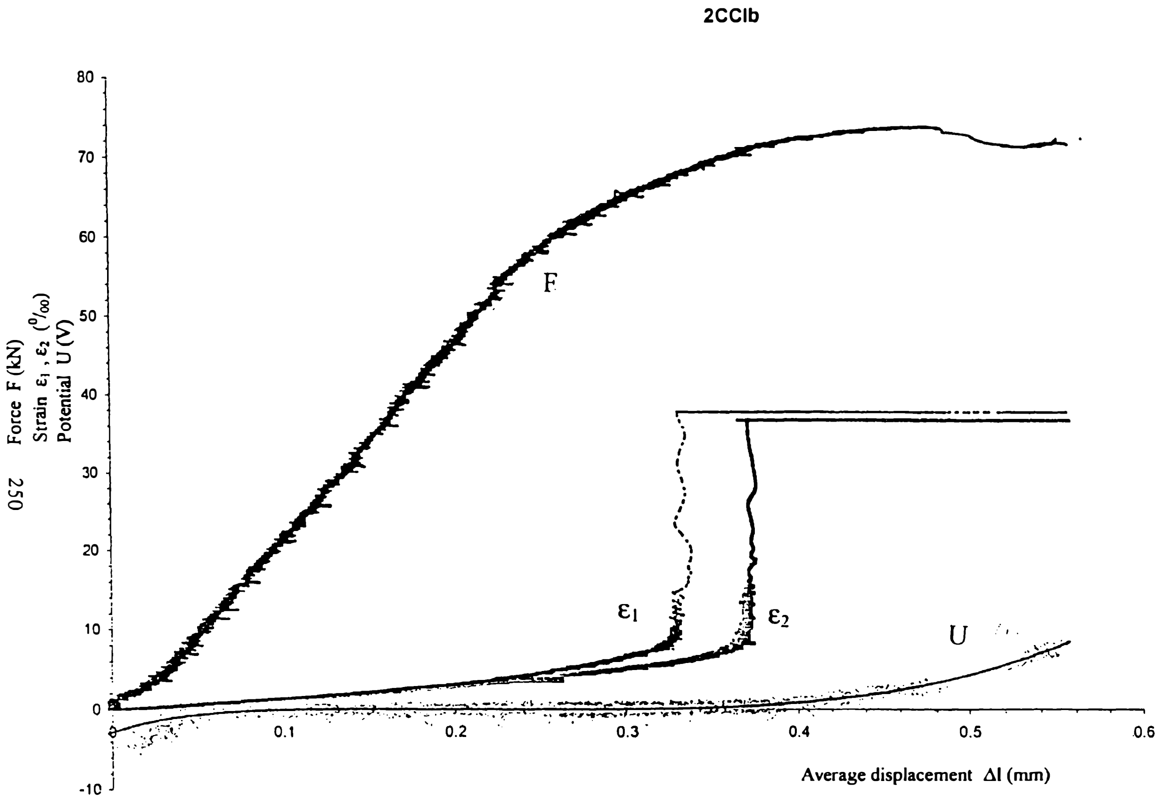

Fig. 2. Plots of variables measured by multiparametric on-line computer system