Calibration methodology of program package for optic measuring of strain and crack resistance determination of compact tension specimens

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Abstract. In the work, the problem of eccentric tension of a compact specimen with a crack was solved by numerical methods. It was proposed to use the results of numerical modeling for setting up and testing the original software package for measuring the deformation of materials by optical methods. The values of the fracture parameters obtained by software coincide with the experimental and numerical results. The proposed testing methodology made it possible to avoid problems with determining the error in the quality of calculation of the optical flow during verification. The dependences of the change of the values of stress intensity factor and J-integral on the applied tensile loading are determined for compact tension specimen with a crack from aluminum alloy D16.

1. Introduction

There are currently various methods for using optical registration of deformation and fracture. Hardware systems using digital image correlation (DIC) techniques are based on fixing changes in a certain static region, the position of which is unchanged during the experiment [1]. One of the promising methods is the new algorithm for detecting cracks in optical images with changing of observation region in the real-time [2,3]. The algorithm allows to change the focus on the surface images and to follow crack growth area in the tracking mode. A further development of this program package is the retrofitting of its software capabilities with algorithms that can determine the energy parameters of a crack, analyze the stress-strain state at the tip, on crack banks and environs falling within the observation area. When detecting and analyzing crack propagation in this case, it becomes possible to analyze fracture mechanisms to obtain a quantitative estimate of parameters, such as stress intensity factor and J-integral.

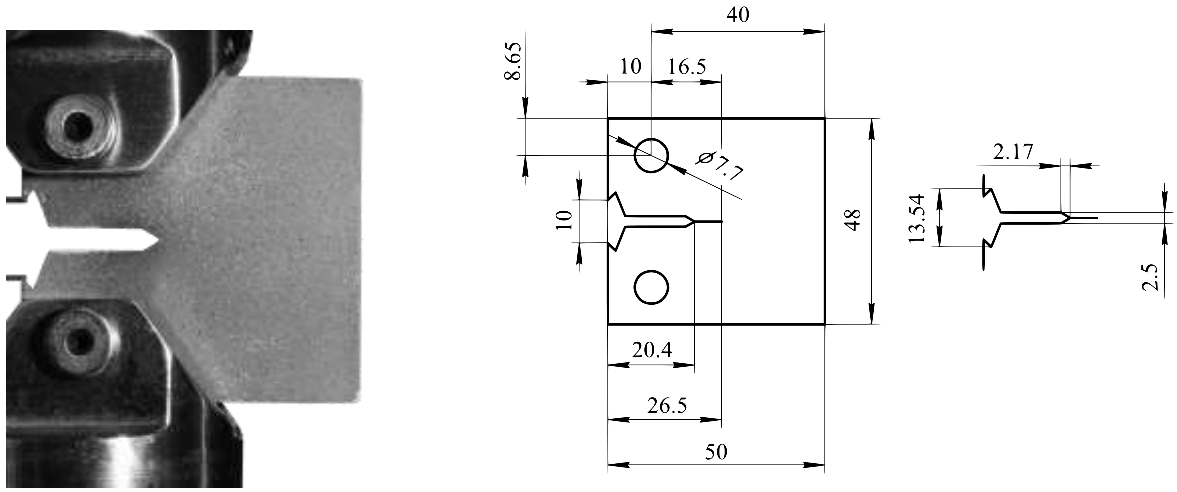
However, at the stage of development such programs, the question arises of the reliability of the obtained values, which depends on the accuracy of the implementation of used algorithms. [4]. The low degree of accuracy of DIC can arise from multiple factors: the low resolution of image data, poor quality of the "speckled" pattern, errors caused by out-of-plane motion, or insufficient smoothing procedures [5] and inaccuracies of program code.

Therefore, it is necessary to verify the results at developing new software packages for measuring the deformation of materials by the optical methods using available experimental or analytical test problems. In this case, methods of mathematical simulation of the stress-strain state in the material of structures implemented using specialized software systems can come to the aid [6-8].

The main purpose of this work was to develop a methodology for verifying a software algorithm prepared for the analysis of optical images, determining the stress-strain state and crack resistant parameters of materials.

2. Investigation methods

An uniaxial tensile experiments were carried out on flat specimens for development an adequate numerical model of the deformation behavior of the material. Tests were conducted using the electromechanical screw-driven testing machine Instron 5582 with the constant nominal strain rate of 10^{-3} s^{-1}. The mechanical properties of the aluminum alloy D16 (According to Nomenclature Russian Structural Materials) with chemical composition: 94 % Al – 1.8 % Mg – 0.91 Mn - ~ 3.29 % other impurities, was determined and a tensile diagram was obtained. The experiments were conducted in accordance with the ASTM standard [9].



(a) (b)

Figure 1. The photography of compact tension specimen (a) in experiment equipment and its drawing (b) with dimensions.

Eccentric tensile experiment was carried out on a compact tension specimen from aluminum alloy D16 with a previously induced fatigue crack. The initial crack 6.1 mm in length was made by the ASTM standard fatigue method [10].

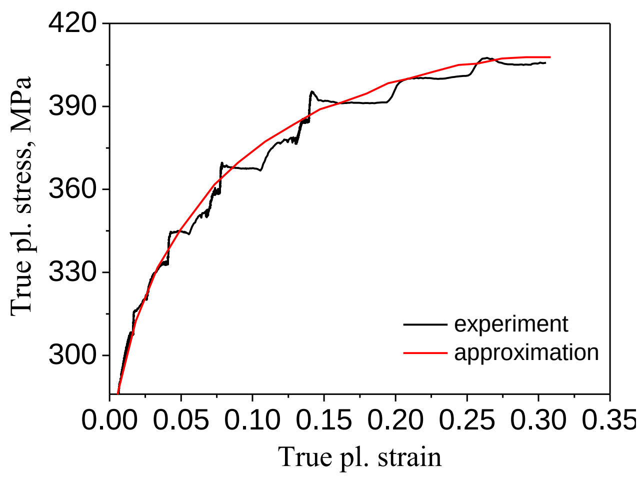


Figure 2. True plastic stress – true plastic strain curves for aluminium alloy D16.

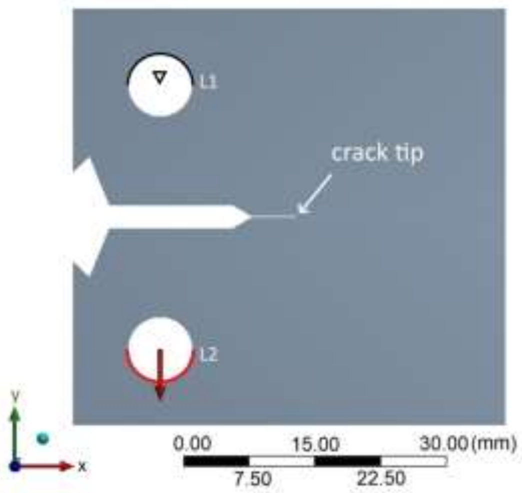


Figure 3. Geometry model of compact tension specimen for FEA.

The experiment was carried out until reaching a loading force of 9100 N, without crack growth. The photography of compact tension specimen in experiment equipment and its drawing with dimensions are depicted in figure 1. For the experiments it was used the BiSS UTM 150 universal servo-hydraulic test system with a force sensor and crack opening displacement gauge. The values of crack resistance parameters were determined in accordance with ASTM standard [11].

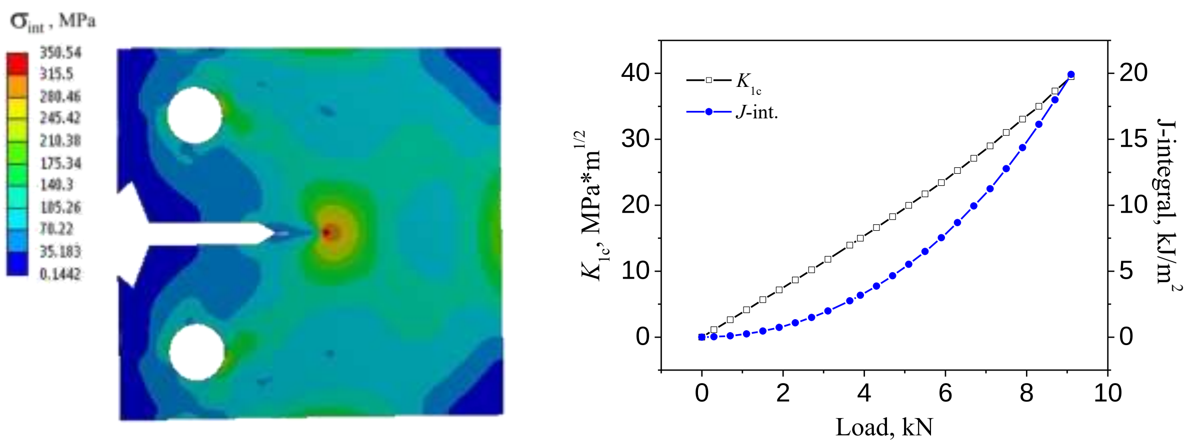
The numerical simulation of eccentric tension of a compact specimen was carried out using the approaches of continuum mechanics and the theory of fracture mechanics. The problem was solved with the using finite element analysis (FEA) in the plane stress state in the Lagrangian formulation. The results of the uniaxial tension experiment of standard specimens of aluminum alloy D16 were used to describe the mechanical behavior of the material. Young's modulus, yield stress, and Poisson's ratio were 70 GPa, 286 MPa, 0.3, respectively. The geometry model was prepared according to the dimensions shown in figure 1b. The model was meshed using a 2D linear triangular element.

It was used a multilinear constitutive equation with isotropic hardening, which approximates the experimental curve of plastic deformation of the used alloy. Experimental data of plastic flow (black line) and approximating curve (red line) which was used in numerical simulation are presented in figure 2a. The experimental conditions were simulated when a compact specimen was loaded with a tensile force of up to 9100 N, without crack growth. The boundary conditions are presented in figure 2b. The line L1 was subjected to displacement constrains and the line L2 was subjected tensile loading conditions along Y-axis.

The results of numerical simulation were used to calibration of vector field parameters of the developed software and verification of the used algorithm.

3. Results of numerical simulation

The result of the described numerical experiment was the values of the parameters characterizing the crack resistance of material, the stress and strain fields in the form of separate digital arrays which contain components of the corresponding values of each calculation node for processing by specialized software systems.



(a) (b)

Figure 4. FEA results: (a) - Von Mises stress field at the maximum load of 9100 N; (b) - numerical calculated evolution of K_{1c} and J-integral values during loading.

Figure 4a shows the Von Mises stress intensity distribution fields in a compact specimen at maximum loading force. A complex stress-strain state is realized at eccentric tension of the sample. The center of plastic deformations develops in the region of the crack tip. The data of crack resistance in crack opening mode were determined on the basis of numerical results. The changes of the values of the stress-intensity factor K_{1c} and J-integral at different time intervals during loading in the form of graphs are presented in figure 4b.

A study was made of the mesh convergence and adequacy of the obtained numerical solution. For this, the numerical results were compared with the experimental results on the extension of a compact specimen made of aluminum alloy D16 with a previously induced fatigue crack.

4. Calibration methodology

In the general case, DIC methods are based on recording the movements of some reference points on the surface of the specimen under study. To do this, an array of dots is preliminarily applied to the sample by spray paint, laser printing, etc. Before the start of the tests, the initial position and the coordinates of the reference points focused in a certain area are fixed programmatically. A series of images with new coordinates of the reference points is recorded in the experiment during deformation of the specimen. Digital data arrays containing information on the movement of all reference points of the observed region are the sources for creating vector fields [12].

The fracture parameters are typically expressed as a line integral. J-integral for known values of displacements, deformations and stresses can be calculated according to the well-known formula proposed by J. Rice in 1968 [13]:

$$J = \int_{\Gamma} \left(w dy - T \frac{\partial u}{\partial x} ds \right),$$

were $w = \int_0^{\varepsilon} \sigma d\varepsilon$; T – load vector, $T = \sigma n$; Γ – contour of arbitrary shape, covering the top of the crack; n – normal vector to Γ; σ ε u – components of the stress, strain tensors and displacement vector, respectively.

However, there is an uncertainty in the choice of the integration path at measuring the values of the stress-intensity factor K_{1c} and the J-integral by the optical method. It is caused by noise due to the presence of experimental errors in determining the displacements. For this reason, one of the ways to increase the noise immunity of determining displacements and the accuracy of the subsequent calculation of the J-integral values is to use various filtering and smoothing algorithms of experimental data [14]. In the study [15], the algorithm for J-integral measurement using the DIC method is described, and an estimation of the noise immunity of the proposed technique is investigated.

It should be noted that rupture of the contour on the crack banks also introduces a noticeable error. Near the discontinuity boundaries, when calculating displacements by the DIC method, errors in their determination arise, and often displacement vectors cannot be correctly determined. The influence of the parameters of this gap, including the development of criteria for determining the optimal distance between the points of the beginning and end of the contour with automated selection, also becomes relevant. Similar problems can be solved using the algorithm for smoothing vector fields and crack detection using the finite element apparatus with a preliminary calculation of acceptable deviations of the displacement values.

The nodes of the numerical model from implementing the finite element method can be taken as reference points of an ideal observation medium for calibrating of program algorithm for measuring the deformation of materials by the optical methods. In this regard, it was proposed to use the results of a computational experiment on eccentric tension of a compact specimen with a crack in the form of node displacements arrays as input parameters for verification of developing software.

The initial position of model nodes and components of the displacement vector for all model nodes at different time intervals stored in text files were processed by calibrated software. The displacement values loaded at individual points were extrapolated to the nodes of the virtual discrete grid, where the values of the strain and stress components were located. In the process of debugging the program, it was chose the discretization step of the vector fields, which allows to more accurately determine the values of the desired parameters [14].

The criterion of achieving the exact solution was the coincidence of the values obtained by numerically and software methods. A comparison of the obtained results is presented in figure 5.

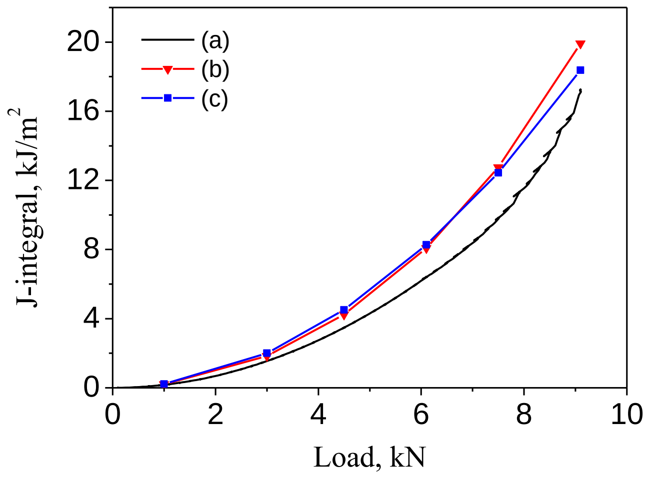
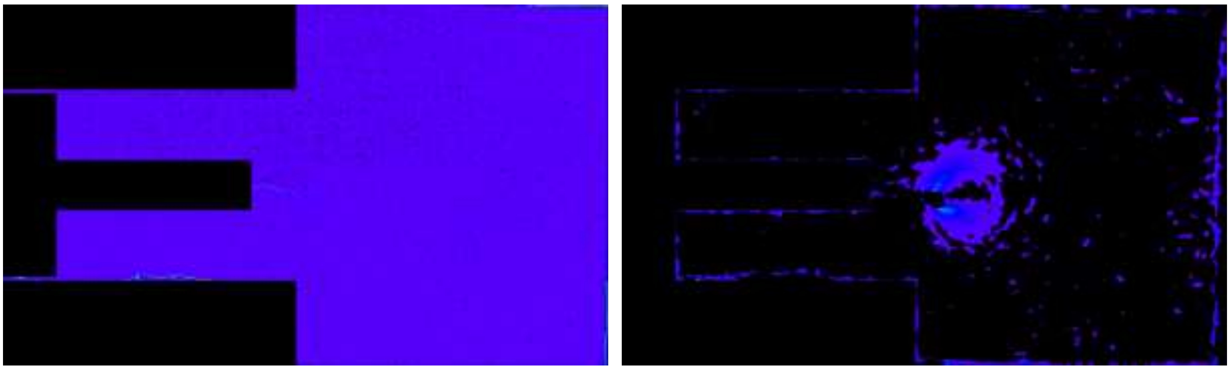


Figure 5. Evolution of the J-integral during loading obtained by three different approaches: (a) - experimental result; (b) - numerical simulation result; (c) – program result.

Figure 6 shows the visualization of the ductility zone with excluded areas (black) of location of the elasticity zone, grips and cut. The calculated values of the stress intensity without postprocessing correspond to the plastic flow throughout the sample (figure 6a). This effect does not correspond to the physics of the processes occurring in the material, which negatively affects the calculation of the J-integral values. Figure 6b shows the result with postprocessing in the form of ductility zone of material, which takes on the distinct form of two petals. This effect corresponds to the physics of the processes occurring in the material, and the calculation of the J-integral along the contours outside the identified zone of ductility gives values which are closer to expected.



(a) (b)

Figure 6. The evaluated Von Mises stress field at the maximum load of 9100 N obtained by program: plastic zone near the crack tip: (a) – without using and (b) – with the using of postprocessing vector field algorithm.

5. Summary

A method for verifying software developed for integration into the original program package for measuring the deformation of materials by the optical method is presented. The algorithm for finding fracture parameters during images processing is based on tracking the displacements of calculation point arrays in the crack opening area. As an ideal example for verification of developed algorithm, it was proposed to use the nodes of the grid model and their displacements obtained as a result of the numerical simulation of the problem of eccentric tension of a compact specimen with a crack as an investigated field of points.

As a result of the adjustment of the algorithm by software methods, changes in the value of the J-integral are calculated depending on the applied load. The obtained values coincide with experimental data with satisfactory accuracy. The advantage of the proposed method for verifying of developed algorithm and setting the optimal discretization of the vector fields of the sought quantities is that the solution is independent of the processing quality of the optical stream. The proposed verification method allows focusing only on mathematical methods and program code at debugging the program.

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