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Digital Image Correlation Method in Experimental Analysis of Fracture Mechanics Parameters

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The principles and examples of state-of-the-art experimental methods for measuring the fracture mechanics parameters are presented in this paper. The methodology of experimental analysis of the fracture mechanics parameters includes investigation of fracture behaviour of metallic materials using modified specimens with initial crack under tensile load, with the primary goal of determining the characteristics of fracture processes for the case of thin plates, using basic fracture mechanics postulates. The methodology also includes the application of experimental fracture mechanics procedures as defined by standards, using three-dimensional stereo-metric mechanical behaviour measurement methods. Fracture behaviour of metallic materials, mainly 316L stainless steel and titanium alloy Ti-6Al-4V specimens, is analyzed by using a digital image correlation (DIC) system for measuring strain and displacement in the material. GOM three-dimensional optical system and Aramis software are used to perform experimental analysis of selected specimens. As this system is used to measure strain and crack tip opening displacement (CTOD) parameter on the modified compact tension specimen C(T) and notch specimens, a basic review of measuring procedures and result processing is given, alongside other possible applications for this system. The presented results show strain and displacement fields during crack tip opening, crack growth, and the moment of fracture of specimens, which are not possible using traditional measurement methods. The analysis of results shows that it is possible to measure displacements during crack tip opening with a great precision, and thus obtain the CTOD parameter. The results show that the selected measuring method obtains good results in the analysis of mechanical behaviour and fracture mechanics parameters of metallic materials.

Key words: **fracture mechanics, metal materials, crack growth, parameters analysis, correlation method, measurement system, optical stereo-metric system.**

Introduction

FRACTURE mechanics is a discipline which requires connecting of theoretical considerations with experimental results, as well as with the occurrence of failures and disasters in structure exploitation. Experimental methods for determining fracture mechanics parameters, including critical value of stress intensity factor K_{IC}, crack tip opening displacement the crack tip opening displacement (CTOD), Rice's contour integral J, were created based on the theoretical analyses and mathematical models of differently shaped bodies with a crack [1-3].

In a more focused sense, the term fracture mechanics is related to an investigation of crack propagation conditions. In a broader sense, it includes a part of strength of materials, which is related to the final stage of the deforming process, caused by the load. On this basis, the strength of materials and structure failure problems are defined as the main subject of fracture mechanics [3-6].

Practical application of fracture mechanics has been based on a two-way interpretation of its parameters: on one hand, they represent the load and structure geometry, including crack geometry, and on the other, they are also a property of the material, i.e. its resistance to crack growth, Fig.1 [3].

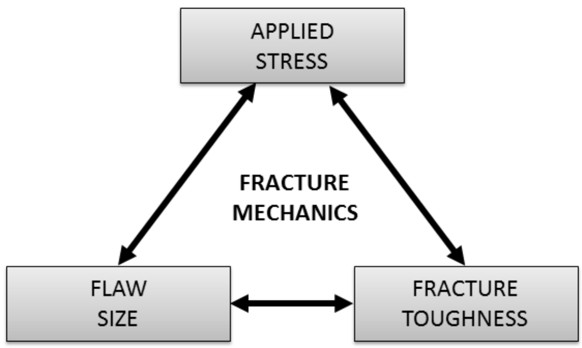

Figure 1. Fracture mechanics triangle [3]

In other words, fracture mechanics became a valuable tool in the hands of engineers whose task was to prevent failure [3, 4, 7, 8]. In the analysis of the behaviour of the material with the crack, it is possible to apply a theoretical [1, 2], numerical [9-13] or experimental approach [7, 14-17].

This paper shows the procedure of experimental investigations and analysis of fracture behaviour of a metal

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material, with application of tension-loaded crack-initiated specimens. Stainless steel 316L and titanium alloy Ti-6Al-4V were selected as characteristic metal materials for a diverse set of engineering applications, the most common being welding, process industries, and shipbuilding. It is necessary to point out that these alloys are used in bioengineering as well, for production of temporary implants, such as bone plates, screws and pins [8, 18, 19].

Presented methodology for the analysis of mechanical behaviour of the crack-initiated materials is based on the application of a system for non-contact optical measurement of strain and displacement, which uses the digital image correlation (DIC) method.

Digital Image Correlation

Digital image correlation (DIC) is an optical, non-contact method for measurement of strain and displacement fields on the surface of the specimen, by comparing images of specimen surface in various stages [20-22]. A reference image is recorded before the loading is applied, and subsequent stages, or steps, are recorded when the specimen is loaded. The displacement field of plane object has two components inside the plane, e.g. u and v, and one component perpendicular to the plane, w. The two components of plane displacement are directly calculated by correlating digital images [20, 22]. The displacement gradients (strain tensors) are then derived by differentiating the space using displacement field data.

This method has found a widespread use in engineering and analytic work, in measuring strain in engineering structures, and analyses of mechanical parameters of engineering materials and biomaterials [15, 23-27]. Using a suitable image processing, the DIC method can quantify even large strains, and is also therefore used to analyse plastic material deformation.

The three -dimensional Digital Image Correlation (3D DIC) method uses two cameras and stereoscopic observation, to obtain full displacement field during the testing procedure, and is shown schematically in Fig.2.

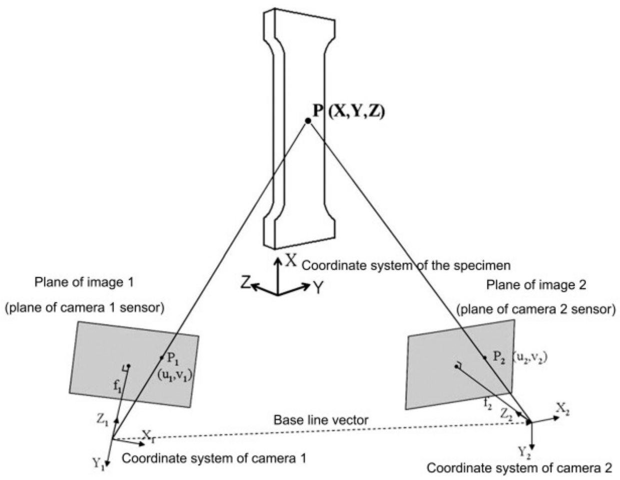

Figure 2. Schematic of the stereometric system.

By using an additional camera which observes the surface from another angle, 3D coordinates of any point can be obtained using triangulation. Subsequently, by comparing the differences between initial images, and images acquired during loading, a full 3D strain field is obtained.

In order to determine the strain at a desired point P, it is necessary to determine the square set of neighbouring pixels around the point, called the subset window (facet), which is used as the pattern in the sample recognition process [20-22]. As the subset window can be deformed in the images recorded during the loading, a photometric transformation is necessary to approximate local strain values. [20, 22]

The following equation is used:

$$\underline{\underline{\mathbf{F}}} = \underline{\underline{\mathbf{R}}} \cdot \underline{\underline{\mathbf{U}}}\,, \tag{1}$$

where $\underline{\underline{\mathbf{R}}}$ is the rotation tensor, and $\underline{\underline{\mathbf{U}}}$ is the strain tensor. The square subset will therefore be affected by uniform strain, and to define z_i translation and strain tensor in two-dimensional correlation algorithm it is necessary to determine six parameters:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{bmatrix} * \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} t_1 \\ t_2 \end{bmatrix} \tag{2}$$

where x, y are coordinates in the non-deformed configuration, and x', y' are coordinates in the deformed configuration. Neighbouring windows of the subset must overlap to achieve a continuous displacement field.

Therefore the “step size” (i.e. the distance in pixels between central points of neighbouring subsets) determines the degree of overlapping. The strain is obtained by differentiating displacement fields.

In order to use the calculations of 2D strains inside a 3D project, it is necessary to define local coordinate systems tangential to local surface, and to calculate strain in 3D, the data must be transformed onto 2D space. Fig.3 shows the definition of local strain directions. The global coordinate system *x-y-z* cannot be used with local strain. Additionally, *x-y-z* system is not parallel to local tangential directions.

To obtain local deformation, an *x'-y'* coordinate system is defined for the non-deformed state, so that for each point (e.g. point P1 in Fig.2): local strain axis *x'* is: tangential to the surface of the local point; parallel to the plane *x-z*; and local strain axis *y'* is: tangential to the surface of the local point; perpendicular to the local axis *x'*.

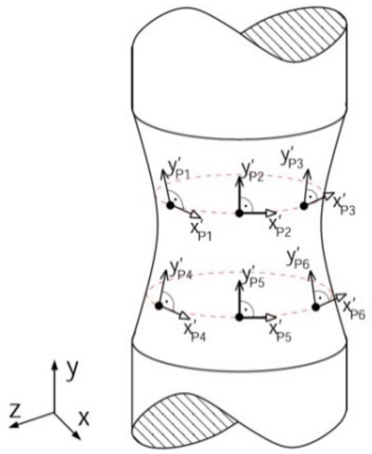

Figure 3. Schematic of the local strain directions

DIC method has considerably advanced over time, so at the moment the displacement resolution is most commonly in the sub-pixel range, from 0.02 – 0.01 pixels, with maximal strain accuracy at 0.02% [22, 23]. Some of the applications for the measuring system are: analysis of material properties, material hardness, component dimensioning, analysis of non-linear behaviour, characterization of creep and aging process, yield strength of materials, verification of numerical FEM (Finite element method) models, analysis of homogenous and non-homogenous materials during strain, and calculation of strain.

Experimental Analysis Procedure

Experimental analysis procedure for determining the fracture mechanics parameters for selected metallic materials presented in this paper is based on an optical methodology measuring system [15, 20-23]. Standard tests of fracture mechanics are applied derived from the modified specimens according to the ASTM International (American Section of the International Association for Testing Materials) standards E1820-08 and E338–03 [28, 29]. In accordance with the limited dimensions of available samples and the idea to investigate the behaviour of fracture of thin plates, the specimens for testing have been extracted from 2 mm thick plates made of 316L steel in first case and titanium alloy in the second one.

Experimental testing arrangement is presented in Fig.4. The main hardware and software components of the system include a sensor with two cameras and a mount which provides sensor stability, an actuator box with power supply for the cameras and image recording control, and a high performance PC system, Aramis application software v6 and GOM Linux 7 operating system or higher [22, 30]. The system uses two matched digital cameras that provide a synchronized stereo view of the specimen.

Figure 4. Experimental testing arrangement

Aramis sensor is placed onto the mount in order to achieve optimal positioning in regard to the specimen. In 3D measurement two cameras (stereo installation) are used, and are calibrated before the measurement. The specimen must reside inside the resulting measurement volume (calibrated 3D space). After the creation of measurement project in the software, images are recorded (monochrome, left and right cameras separately) during specimen loading steps.

Calibration is a measurement process during which the system is adjusted using a calibrator in order to obtain dimensional consistency. Aramis system uses two calibrators: calibration plates for small measurement volumes, as shown in Fig.5, and calibration crosses for large measurement volumes.

Before the start of the first measurement, it is necessary to calibrate the appropriate measurement volume, with the recommended limit of successful calibration deviation of 0.01 to 0.04 px [22, 30]. If, due to different volumes, it is necessary to change the distance to specimen, or the angle between the cameras, a sensor recalibration must be performed.

During sensor calibration, sensor setting is obtained, meaning that the distance and angle between the cameras are determined. Additionally, lens properties are entered (e.g. focal length, lens distortion). Measurement volume depends on the size of the specimen, or the size of the desired area to analyze. It is necessary to select a measurement volume inside which the specimen, or the desired area, fills the entire image as much as possible.

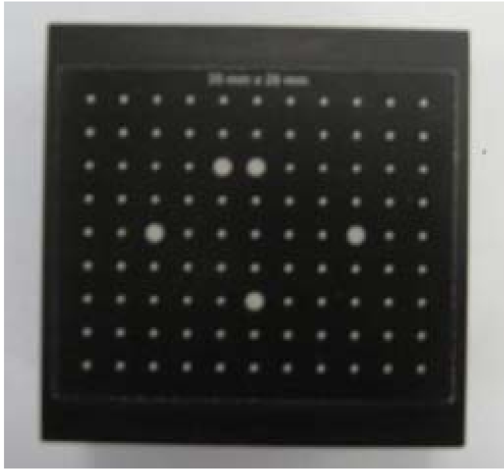

Figure 5. An example of a calibration plate used in experimental investigation

System calibration using calibration plates was performed prior to the start of the experiment. The chosen volume was based on the specimen dimensions and in accordance with the tables in the instruction manual [22, 30]. An example of calibration plate chosen for the measurement is shown in Fig.5.

If necessary, the first step is to apply a white, matte foundation on the specimen, and then spray on a black random dot pattern, i.e. create a high contrast random dot pattern. For smaller measurement volumes, a smaller pattern is needed than for larger volumes. To ensure that the sprayed-on pattern conforms to the selected measurement volume, printed reference patterns are supplied with the system.

Specimens prepared by placing reference points used in the experimental analysis are shown in Fig.6.

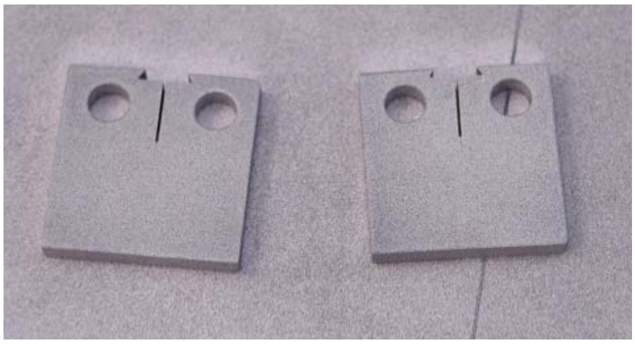

Figure 6. Prepared C(T) specimens

After the successful calibration of the measurement system and the specimen, the measurement procedure was performed, including the creation of a new project, setting the recording speed and lighting around the specimen.

After the evaluation surface (computational mask) is determined, and a point of origin is selected, the measurement project is calculated. After the calculations have finished, the measurement results can be presented as a 3D view. From these results all other representations are derived, such as statistical data, reports, etc. Aramis recognizes the specimen surface structure on the digital camera images and allocates the coordinates to pixels on the images. The first image in the measurement project corresponds to the non-deformed state of the specimen.

Results and discussion

Strain measurement results can be viewed using reports, and several report templates are available to present the results in a simple way. Standard reports include results, diagrams and camera images, with the option to create new report templates.

The results of this analysis show the major strain field on the specimen under tensile load during crack tip opening, crack growth and fracture, as well the CTOD results.

Although CTOD parameter has an experimental character, it is widely accepted because even in complicated problems it is easily determined and gives good results. In the area of a small scale yielding (SSY) it is possible to connect it with K_I [3, 22].

$$\delta = \frac{K_I^2}{mE\sigma_T} = \frac{G}{m\sigma_T} \qquad (3)$$

In order to determine critical CTOD using BSI (British Standards International) standard it is necessary to fortify the beginning of the crack growth, i.e. to determine the relevant value of δ_t using definitions recommended according to the standard. Used value is δ_m, i.e. value δ_t when reaching the highest load in zone of plasticity.

Several examples of the results observed by using this methodology are presented on the following diagrams, and the CTOD values, which are the fracture mechanics parameters of the examined material, can clearly be seen. CTOD is monitored by Aramis and the major strain field of the titanium alloy compact tension specimen $C(T)$ specimen is shown in Figures 7 and 8, and major strain field of the titanium alloy notch specimen is show in Fig.9.

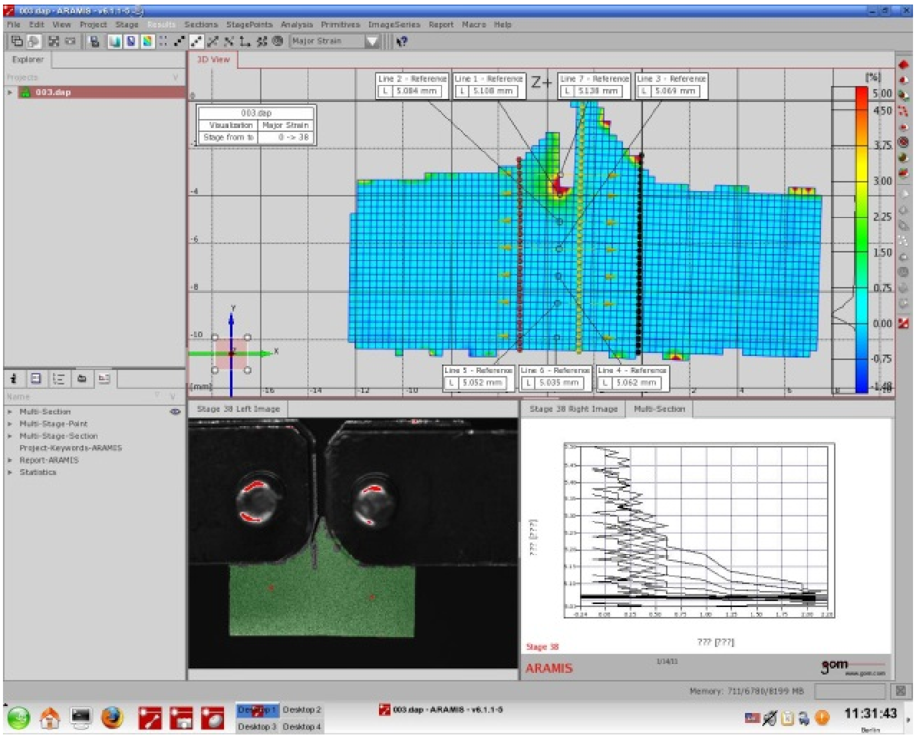

Figure 7. Results for C(T) specimen during crack propagation

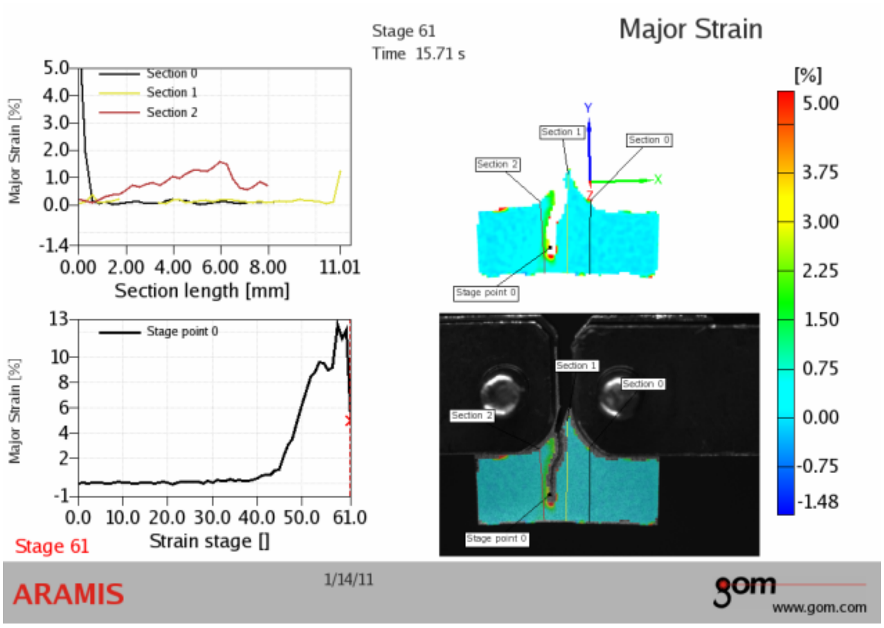

Figure 8. Results for C(T) specimen at the moment of fracture

The major strain field and CTOD values during the crack tip opening for titanium alloy C(T) specimen are presented in Fig.7.

The major strain field of the titanium alloy C(T) specimen at the moment of fracture is shown in Fig.8.

The major strain field and CTOD values during the crack tip opening for titanium alloy notch specimen are presented in Fig.9.

With the optical measurement techniques (e.g. Aramis, Argus), displacement and strain are calculated at the specimen surface only, meaning that the calculations are limited to local strain, which is tangential to specimen surface. As there is no additional information on the values perpendicular to the specimen surface, it is not possible to calculate the total 3D strain tensor. In this case, the calculation of thickness change is based on the assumption that the material volume remains constant during loading.

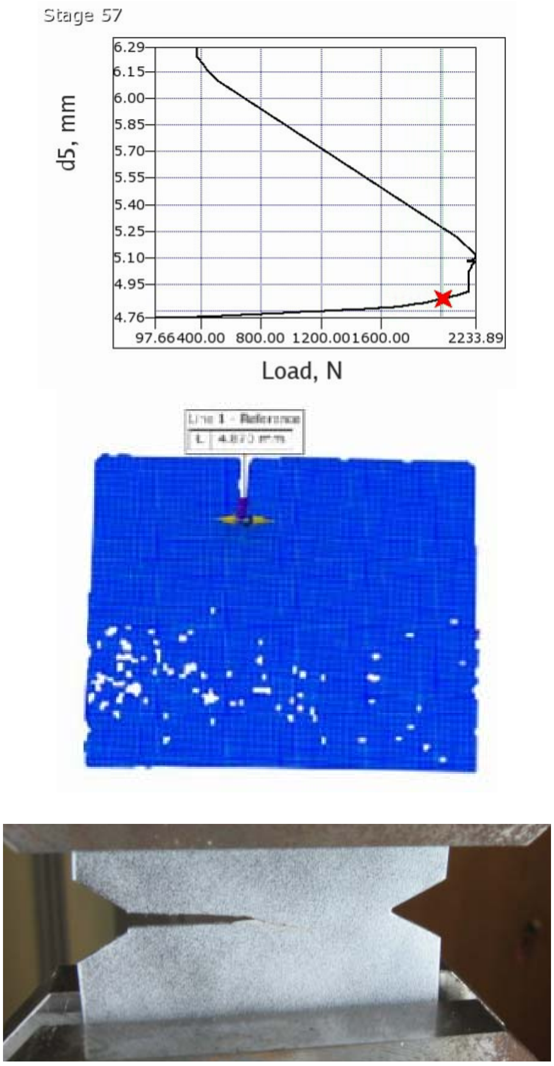

Figure 9. Results for notch specimen

Conclusions

The described experimental analysis procedure provided the results describing the fracture behaviour and mechanical parameters of metallic biomaterials. Figures demonstrate that the strain is the largest at the site of the crack tip and in the direction of its growth, as expected. Additionally, by comparing strain fields in the figures at the time of the crack tip opening and immediately before specimen fracture, it is possible to follow the material stress effectively.

Experimental methods shown in the course of this paper, which were used during the laboratory analyses, including three-dimensional experimental optical analysis of the fracture behaviour of a characteristic metallic biomaterial and calculating its strain field, were performed using licensed GOM optical measurement systems and Aramis data processing software. By using this method it is possible to perform an analysis of surface strain on the actual component geometry, which is not possible using the traditional measurement equipment. Additionally, using this method in standard experimental fracture mechanics tests enables direct observation of selected relevant fracture mechanics parameters, such as the CTOD parameter, and the display of the crack growth in the biomaterial.

Measurement of the mechanical parameters and complete strain and displacement fields of implant biomaterials presents a significant problem if existing measurement technologies are used. It is necessary to obtain three-dimensional measurement results, having in mind that non-linear deformations are visible on the object inside the measuring space. Measurement systems for the optical three-dimensional strain analysis represent the most advanced measurement method for understanding mechanical behaviour of biomaterials and components independent of their materials, size and geometry, and as such can supplement other state-of-the-art analysis methods. By using this kind of measurement system, the actual component geometry is analyzed, which is not possible using the traditional measurement equipment, such as extensometers, or displacement sensors (LVDT).

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Metoda korelacije digitalnih slika u eksperimentalnoj analizi parametara mehanike loma

U okviru rada su predstavljeni principi i primeri savremenih eksperimentalnih metoda za određivanje parametara mehanike loma. Metodologija analize i određivanja parametara mehanike loma obuhvatila je analizu ponašanja metalnih materijala u odnosu na lom primenom modifikovanih epruveta mehanike loma, sa inicijalnom prslinom i zateznim opterećenjem, i imala je za cilj pre svega određivanje karaktera tih procesa u slučaju problema tankih pločica, uz korišćenje osnovnih postulata mehanike loma. Metodologija uključuje primenu eksperimentalnih postupaka mehanike loma definisanih standardima, uz primenu metode za trodimenzionalno stereoskopsko merenje mehaničkog ponašanja materijala. Pomoću sistema za korelaciju digitalnih slika (Digital Image Correlation, DIC) za ispitivanje deformacija i pomeranja u materijalu ispitani su parametri mehanike loma metalnih materijala, pre svega epruveta od 316L nerđajućeg čelika i titan legure Ti-6Al-4V. 3D optički sistem GOM i softver Aramis su korišćeni za izvođenje eksperimentalne analize na pripremljenim epruvetama. Pošto se ovaj sistem koristi za merenje deformacija i parametra pomeranja otvaranja vrha prsline CTOD na modifikovanim kompaktnim epruvetama za zatezanje C(T) i epruvetama sa zarezom, dat je i kratak pregled mernih procedura i procesiranja rezultata, kao i moguće primene ovog sistema. Prikazani rezultati daju pregled polja deformacija i pomeranja tokom otvaranja vrha prsline, rasta prsline i u trenutku loma epruvete, što nije moguće putem tradicionalnih metoda merenja. Analizom rezultata pokazano je da je sa velikom preciznošću moguće izmeriti pomeranja tokom otvaranja vrha prsline i dobiti CTOD parametar. Rezultati pokazuju da odabrana metoda pruža dobre rezultate u analizi mehaničkog ponašanja i određivanju parametara mehanike loma metalnih materijala.

Ključne reči: **mehanika loma, metalni materijali, rast prskotine, analiza parametara, metoda korelacije, merni sistem, optički stereometrijski sistem.**

Метод корреляции цифрового изображения в экспериментальном анализе параметров механики разрушения

В статье представлены принципы и примеры современных экспериментальных методов для определения параметров механики разрушения. Методология анализа и определения параметров механики разрушения включала анализ поведения металлических материалов по отношению к трещине с использованием модифицированных пробирок механики разрушения с начальным трещинообразованием и растягивающим напряжением и в первую очередь была направлена на определение характера этих процессов в случае проблем

**тонкой черепицы с использованием основных постулатов механики разрушения.
Методология включает применение экспериментальных методов механики разрушения, определённых стандартами, с использованием метода трёхмерных стереоскопических измерений механического поведения материалов. Используя систему цифровой корреляции изображений (Digital Image Correlation, DIC) для проверки деформаций и смещений в материале, были испытаны параметры механики разрушения металлических материалов, в частности пробирок из нержавеющей стали 316L и титанового сплава Ti-6Al-4V. 3D-оптическая система GOM и программное обеспечение Aramis использовались для проведения экспериментального анализа на подготовленных пробирках. Поскольку эта система используется для измерения деформаций и параметров движения открытия крекинг-наконечника CTOD на модифицированных компактных пробирках C и T, даётся краткий обзор процедур измерения и обработки результатов, а также и возможное применение этой системы. Представленные результаты дают обзор полей деформаций и смещений при открытии наконечника трещины, роста трещины и во время отказа пробирки, что невозможно провести традиционными методами измерения. Анализ результатов показал, что с высокой точностью можно измерить движения во время открытия наконечника трещины и получить параметр CTOD. Результаты показывают, что выбранный метод даёт хорошие результаты при анализе механического поведения и при определении параметров механики разрушения металлических материалов.**

Ключевые слова: **механика разрушения, металлические материалы, трещинообразование, анализ параметров, метод корреляции, измерительная система, оптическая стереометрическая система.**

Méthode de corrélation des images digitales dans l'analyse expérimentale des paramètres de la mécanique de fracture

Les principes et les exemples des méthodes expérimentales contemporaines pour la détermination des paramètres de la mécanique de fracture sont présentés dans ce papier . La méthodologie de l'analyse et la détermination de la mécanique de fracture a inclus l'analyse du comportement des matériaux en métal par rapport à la fracture faite par application des éprouvettes modifiées de la mécanique de fracture avec la fissure initiale et la charge de tension . Son but principal était la détermination du caractère de ces processus pour les cas des plaques minces avec l'emploi des postulats basiques de la mécanique de fracture. Cette méthodologie comprend aussi l'utilisation des procédures expérimentales de la mécanique de fracture définies par les standards et en appliquant les méthodes pour le mesurage stéréoscopique à trois dimensions du comportement mécanique des matériaux. A l'aide du système pour la corrélation des images digitales (DIC) pour l'examen des déformations et du déplacement dans le matériau on a examiné les paramètres de la mécanique de fracture pour les matériaux en métal, avant tout les éprouvettes en acier inoxydable 316L et l'alliage titane Ti-6Al-Av. Le système optique 3D GOM et le logiciel Aramis ont été utilisés dans l'analyse expérimentale des éprouvettes préparées. Comme ce système s'emploie pour le mesurage des déformations et des paramètres de déplacements de l'ouverture du sommet de la fissure CTOD chez les éprouvettes compactes modifiées pour la tension C(T) et chez les éprouvettes entaillées on a donné un bref compte-rendu des procédures de mesurages, des résultats obtenus et des applications possibles de ce système. Les résultats présentés démontrent les champs de déplacements et des déformations lors de l'ouverture du sommet de la fissure ainsi que la croissance de la fissure au moment de fracture de l'éprouvette, ce qui n'est pas possible par les méthodes traditionnelles de mesurage. L'analyse des résultats prouve qu'il est possible de mesurer les déplacements pendant l'ouverture du sommet de fissure avec grande précision et obtenir les paramètres CTOD. Selon les résultats obtenus la méthode choisie offre de bons résultats dans l'analyse du comportement mécanique de fracture des matériaux en métal.

Mots clés: **mécanique de fracture, matériaux en métal, croissance de fissure, analyse des paramètres, méthode de corrélation, système de mesures, système optique stéréométrique.**