EXPERIMENTAL INVESTIGATION OF SPACE-TIME INHOMOGENEITY AT ELASTO-PLASTIC AND POSTCRITICAL DEFORMATION PROCESSES OF MATERIALS BY DIGITAL IMAGE CORRELATION TECHNIQUE

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Abstract

In the present work are presented some results of complex experimental investigation material behavior at elasto-plastic and postcritical deformation stages by using non-contact digital image correlation technique. High efficiency of DIC method was shown for different material types, inclusive of composite materials. Results contain accuracy estimation data, space-time inhomogeneity, such as waves of localized plastic strain, necking effect, heterogenous strain fields.

1 Introduction

1.1 Digital image correlation technique

Digital image correlation (DIC) is effective non-contact, computer-vision-based, specimen surface displacement and strain fields measuring technique by correlating digital images before and after loading [1]. The main idea is that we can measure strain by matching the reference subsets in the undeformed digital image with the target subsets in the deformed digital image.
In present paper was contemplated using of three-dimensional digital video-system Vic-3D (figure 1). Its software is based on digital image correlation technique. The system allows estimating out-plane displacement and strain fields on surface of different materials, such as metals and alloys, plastics, composite materials, rock and etc [2-5]. The video-system includes two pairs of digital monochrome DCD cameras with 1.4 and 4.0 resolutions. The two cameras are mounted on a rigid bar to avoid relative motion of the cameras. Also the system has interchangeable lens with focal distances in the range from 17,4 to 192,0 mm, two illumination systems, a synchronizing module and calibration grids. Maximum speed of taking pictures is 15 images per second at full resolution.

1.2 Inhomogeneity of deformation processes in different materials

With the view of material hardening and accident prevention of structural components a big quantity of different optical methods of deformable solid mechanics are used for analysis of stressedly-deformed materials mode, investigation of displacement and strain fields

inhomogeneity. Inhomogeneity of deformation processes can be caused by stress concentrators, inclusions and interstices in material, localized plastic strain and others.
The aim of this research was to investigate different types of heterogeneities in deforming processes at elasto-plastic and postcritical deformation stages by using digital image correlation technique.

2 Materials and testing methods

2.1 Accuracy estimation of 3-D DIC measurement system Vic-3D

Accuracy of optical measurement system depends on technical characteristics of lenses and digital cameras (resolution, sensor sensitivity, maximum capture speed). Also quality of specimen surface preparation, right setting of image definition, calibration accuracy can influence on test results as well. Because the measurement system Vic-3D is three-dimensional, so rate of angle between both cameras is very important too.
For the purpose accuracy estimation of the measurement system Vic-3D we carried out range of tests on the universal servo-hydraulic biaxial test system Instron 8850 with using of the mounted dynamic extensometer Instron 2620-601 (figure 1) [4]. According to Instron test certificate of the extensometer, maximum error is +0.059%, −0.022% of full scale. Its base is 50 mm; maximum rate of extension/compression is ±5 mm.

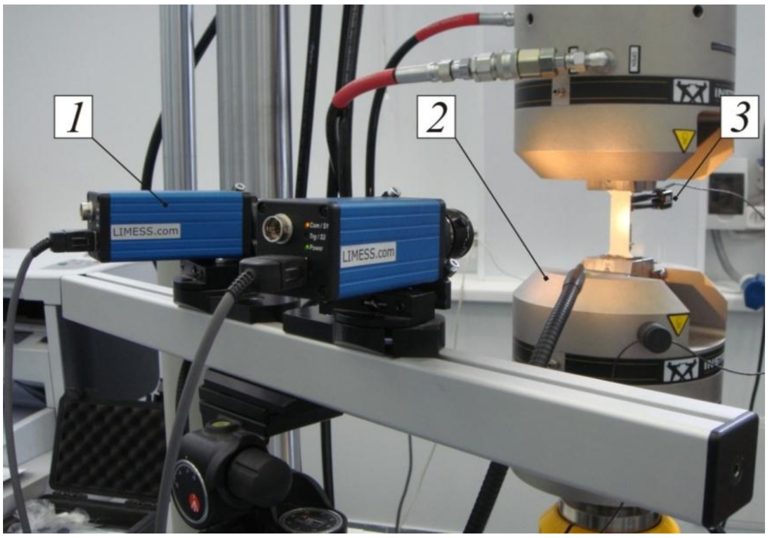

Figure 1. 3-D DIC measurement system Vic-3D (1), universal servo-hydraulic biaxial test system Instron 8850 (2), mounted dynamic extensometer Instron 2620-601 (3)

Estimation procedure of measurement accuracy consisted in synchronous strain registration on surface of flat specimen from one side with a help of the video-system and from opposite side – by the mounted extensometer (figure 2, a). It should be taken into account that data from the extensometer depends on accuracy of its fixing, alignment error, not-full contact of extensometer’s knives with specimen surface. Also there are possible differences in data between two measurement items due to strain gradient.
Registration of axial strain by the video-system Vic-3D was carried out with using of additional software module ‘Virtual Extensometer’. The main difference between ‘Virtual Extensometer’ and the mounted extensometer, that the first one is used after tests during analysis of results. So if we use ‘Virtual Extensometer’, it is possible to mount several similar extensometers on one specimen (figure 2, b).
Mechanical tests were carried out on aluminum flat dog-bone specimens (thickness is 1.9 mm, width is 20 mm, work length is 50 mm) with extension speed 1.0 mm/min.

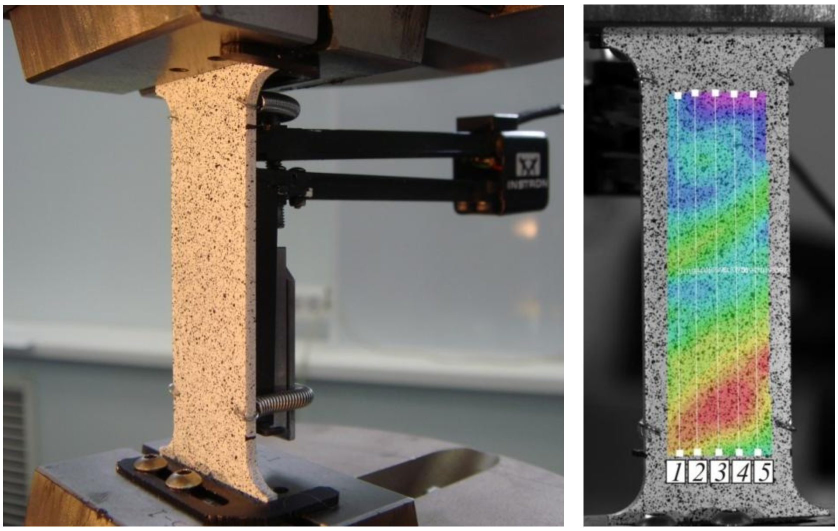

Figure 2. Picture of the specimen with the mounted extensometer (a), axial strain registration by using of 'Virtual Extensometer' (b)

On figure 3 is shown that the time-strain third curve, which was acquired by the extensometer, practically coincides with the second curve, which was acquired by the video-system Vic-3D, on initial deformation stage. The reason of a big number of teeth on load diagram (figure 3) is the effect of intermittent deformation, which is typical for aluminum alloys.

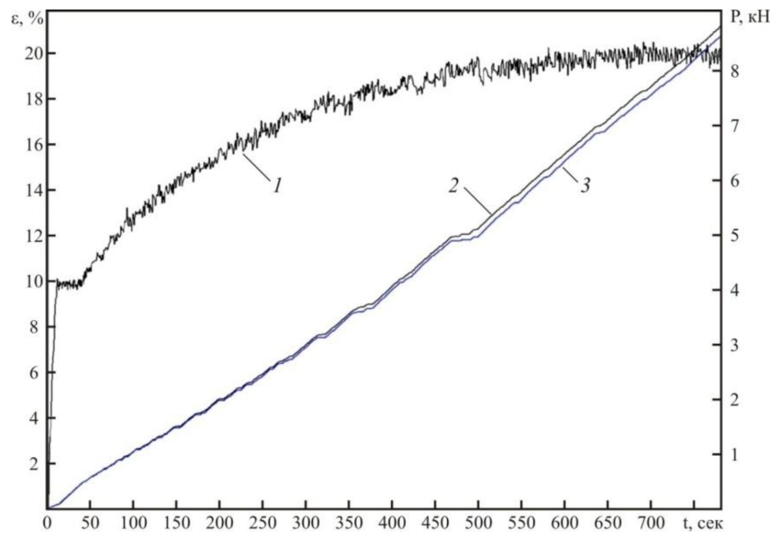

Figure 3. Time-load curve (1), time-strain curve, acquired by the video-system (2), time-strain curve, acquired by the mounted extensometer (3) during axial tension of flat aluminum specimen

On the hardening deformation stage difference in data between the DIC measurement system and the extensometer is increasing (figure 3). Results of tests on axial tension of flat aluminum specimens shows that using digital image correlation measurement system allows getting exact results with comparable accuracy. In addition, the video-system fixed displacement and strain fields evolution, waves of localized plastic strain. The fully information about these effects is mentioned hereinafter.

2.2 Results of experiments

With the aim of complex experimental investigation of strain fields' evolution at inelastic deformation stages different mechanical tests were carried out (table 1). Tests were conducted on the universal servo-hydraulic biaxial test system Instron 8850 and the universal electromechanical test system Instron 5882 in the Center of Experimental Mechanics of Perm National Research Polytechnic University (Russia).

Material	Specimen form	Test	Type of space-time inhomogeneity
Aluminum alloy	Flat dog-bone specimen	Uniaxial tension	Waves of localized plastic strain
Low-carbon steel	Solid cylindrical dog-bone specimen	Uniaxial tension	Strain localization (necking)
Fiberglass composite material	Scaled-down panel	Uniaxial tension	Inhomogeneity of strain fields

Table 1. Types of strain fields heterogeneities, researched by digital image correlation.

2.2.1 Strain fields on aluminum flat dog-bone specimen surface

There were carried out tests on uniaxial tension of flat aluminum dog-bone specimens with different extension speed (table 2).

Specimen quantity	Thickness	Width	Work length	Extension speed
4	1.9 mm	12 mm	50 mm	0.5 mm/min, 1 mm/min
4	1.9 mm	20 mm	50 mm	1 mm/min, 5 mm/min, 10 mm/min

Table 2. Parameters of aluminum specimen tests.

It is interesting to estimate the influence of extension speed and specimen geometry on processes of forming and evolution waves of localized plastic strain on surface. On stage of postcritical material deformation were fixed and determined different wave types of localized plastic strain by using digital image correlation measurement system Vic-3D. Was calculated motion speed, angle between specimen axis and wave line. As an example, on figure 4 are shown the axial strain fields at different load levels: 4.694 kN, 5.229 kN, 8.322 kN.

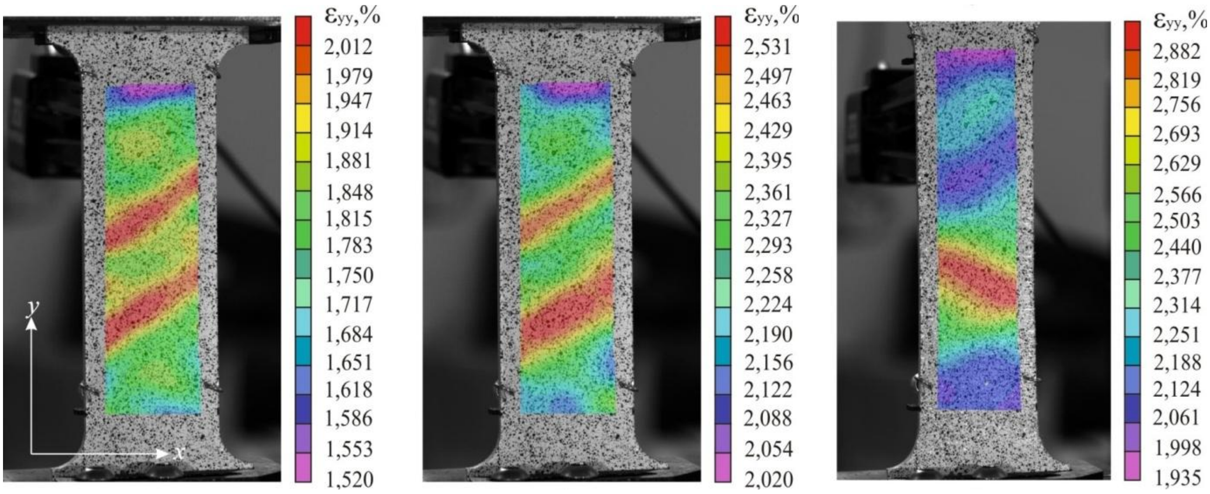

Figure 4. Examples of axial strain fields, which were got by digital image correlation technique

2.2.2 Results for low-carbon steel cylindrical specimens

The uniaxial tension was carried out with constant macro deformation speed 2% per minute on cylindrical specimens with different work lengths. On figure 5 is shown stress-strain curve for 16 mm length specimens. Specimen diameter is 9.5 mm. These curves consist of yield drop forming stage, material hardening and long postcritical stages as well.

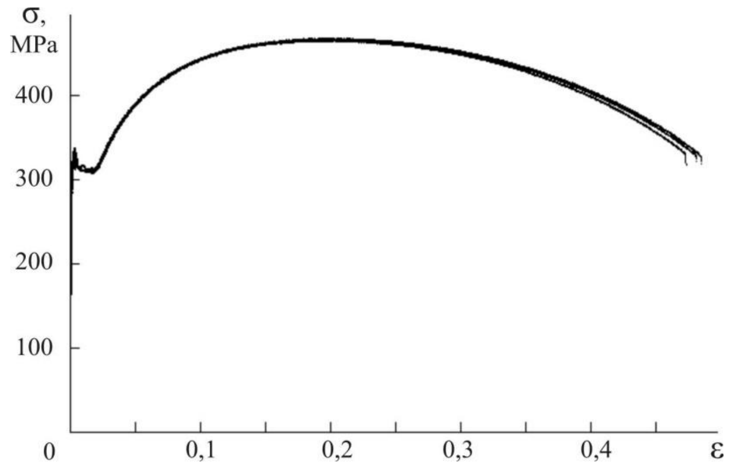

Figure 5. Stress-strain curves for low-carbon steel specimen at uniaxial tension

Shape changing of cylindrical specimen with 16 mm work length on different deformation stages (I–VI) is presented on figure 6. Apparently, localization of strain in central part of specimen occurs in consequence of plastic deformation, also we could observe the necking effect. Material deforms irregularly.

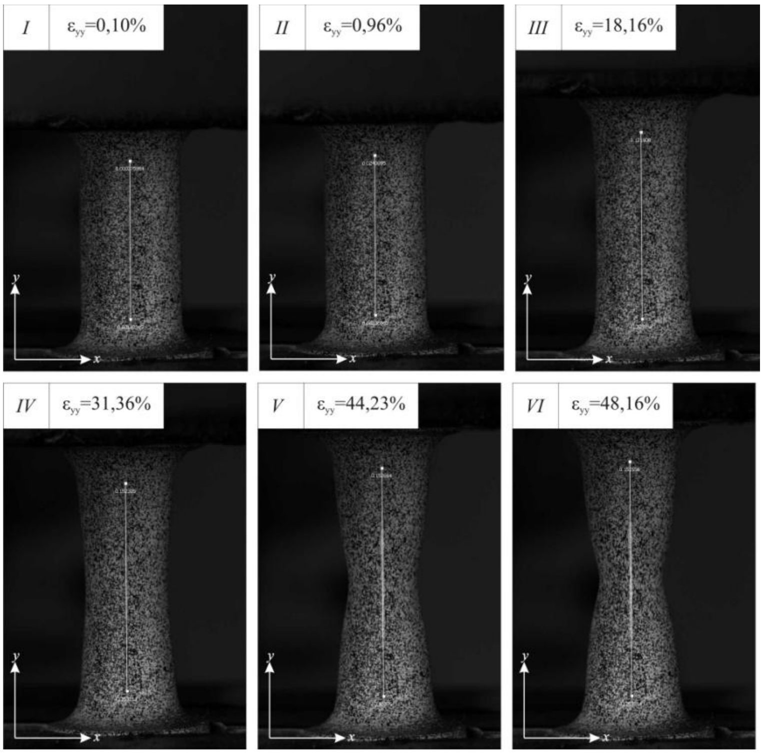

Figure 6. Changing of shapes of cylindrical specimens with 16 mm test portion length on selected stages of deformation (*I–VI*)

For each deformation stage mean value of axial strain was experimentally analyzed at selected specimen base by calculating of relative displacement of peripheral points, by using the additional software module 'Virtual Extensometer'. Also were fixed changing of axial strain distribution lengthwise of specimen during test (figure 7).

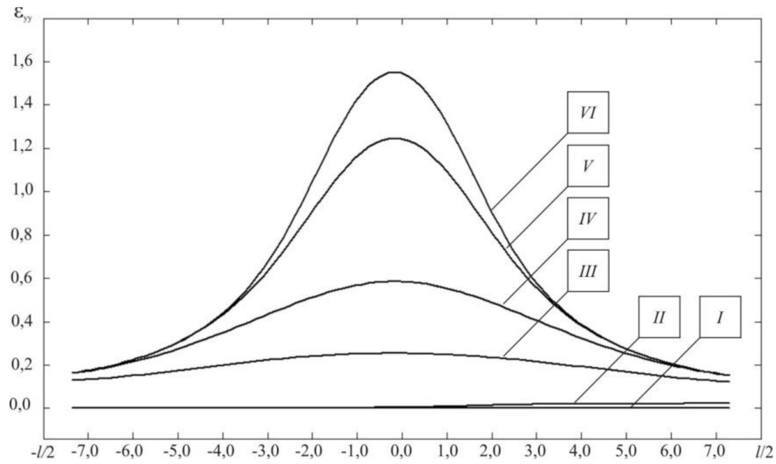

Figure 7. Distribution of axial strain lengthwise of cylindrical specimen with 16 mm work length on selected deformation stages labeled from (I) to (VI)

Localization of plastic strain occurs not only at postcritical deformation stage but at the stage of material hardening. At that, mean values of axial strain were much less values of axial strain in central part of specimen — in area of localization of plastic strain. It means that there was elastic unloading of peripheral parts of specimen.

2.2.3 Strain fields on fiberglass composite panel surface

Digital image correlation technique allows estimate strain fields on composite material surface. It is very important to use the non-contact measurement method if we need to test nonstandard or large capacity composite specimens. It is impossible to use usual mounted extensometers, so for getting exact data from tests DIC method should be used.

For example on figure 8 are presented strain fields on surface of fiberglass composite scaled-down panel under uniaxial tension.

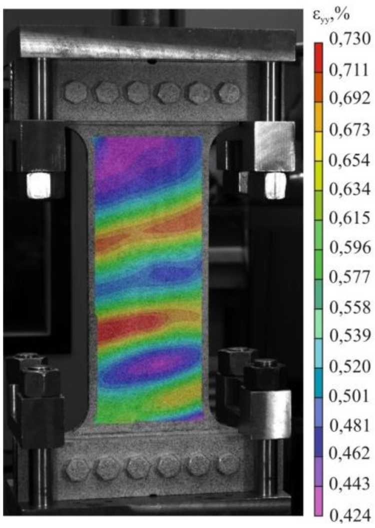

Figure 8. Strain fields on surface of composite scaled-down panel under uniaxial tension

Summary

In the present work are presented some results of complex experimental investigation material behavior at elasto-plastic and postcritical deformation stages by using non-contact digital image correlation technique. High efficiency of DIC method was shown for different material types, inclusive of composite materials. In work are presented tests results on estimate of measurements accuracy, which were conducted by synchronous using optical system of displacement and strain fields analysis and dynamic extensometer. Results contain space-time inhomogeneity, such as waves of localized plastic strain on aluminum flat specimen surface, necking effect on low-carbon cylindrical specimens, heterogenous strain fields on surface of fiberglass composite scaled-down panel.

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