PHOTOGRAMMETRIC TECHNIQUE FOR THE DETERMINATION OF THE MOMENT IN TIME AND THE PLACE OF THE LOSS OF STABILITY DURING THE PLASTIC DEFORMATION OF SHEET METAL

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Abstract: *An experimental study establishing a technique for the contactless optical determination of the local plastic formability limit on the loss of stability of sheet metal has been conducted. The possibilities for the recording of the time instant and the place of the localisation of the deformation based on the changes in the optical images of the surface have been examined. An optical criterion for the determination of the time instance and the place of the loss of stability derived through a correlation analysis of the images has been proposed. The experimentally obtained results have been presented and analysed.*

Keywords: *stable formability limit, loss of stability, photogrammetry,* correlation *analysis, digital image correlation.*

1. Introduction

Upon the implementation of sheet stamping operations with a variety of variable schemes can be observed an uneven distribution of stress, strain and strain rates in the volume of the metal during the entire technological process. The influence of a large array of factors greatly hampers the general summary of the formability and localisation of the plastic deformation in particular and is the reason for the lack of established unified methodologies for rational technological design of tools and technologies for sheet stamping.

For the manufacture of complex products with irregular shape with the realisation of combinations of various operations throughout the entire range of variation of the stress state, the use of marginal sustainable formability diagrams (MSFD) ensures the maximum usage of the plastic resource of the material. In these cases the registration of the exact moment of the beginning of the focused macrolocalisation is crucial, and given the associated technical difficulties, the possibility for the creation of the diagrams and the practical application of the existing criteria are insufficiently studied [Генов, 2004] . In this regard of particular interest is the study of the various aspects of focused localisation that leads to the loss of stability of the plastic formability.

In the laboratories “Plasticity and Fracture of Materials” and “Mechanical Testing of Materials” at the “Materials Science and Technology of Metals” Department at the Technical University – Sofia has been conducted years of research on the deformability of sheet metal [Генов, 2007; Stoilov, 2009; Пригоровский, 1983]. One of their main goals is the study of the options for control and management of the technological process and facilitation of the creation of marginal formability diagrams (MFD) and MSFD. The efforts are focused on the establishment of a simple methodology for determination of the moment in time and place of the loss of stability, based on contactless measuring of the deformations.

There are a number of practically established traditional contactless experimental methods for the study of displacements and deformations that differ in the complexity of the preparation and the study itself, the experimental apparatus used, the nature of interaction with the object and the material from which it is made, the sensitivity, the accuracy, the reproducibility and the comparability of the results [Пригоровский, 1983; *Heymann, 1986; Khan, 2001*]. They are based on different optical effects or on the optical recording of images of real objects.

The experiments conducted so far for the determination of the moment in time and place of the loss of stability by optical means has used as optical criterion for the determination of the moment of the loss of stability of the sheet metal the integral intensity of the reflected light from the metal surface [Хубенов, 2008]. Its variation as a result of the changes during the course of the deformation process in the topography of the surface, when registered properly, can be used as an indicator of the occurrence of the focused localisation.

This work presents a new series of studies carried out jointly with the “Mechanics of the Deformable Solid Bodies” Division at the Institute of Mechanics at the Bulgarian Academy of Science, related to the contactless determination of the marginal sustainable formability of sheet metal based on an optical criterion for the loss of stability. They include the capture of photographic images of the surface with subsequent correlation analysis through the use of software for digital processing and analysis of the images recorded with the digital camera.

2. Methodologies

The sustainability of the formability of the sheet metal is a key condition for obtaining high quality stamped items. One of the most interesting, practically important and not fully explored to date issue that is inextricably linked to the study of plastic flow is its tendency to spontaneous localization, which in the limiting case (when exceeding a given critical value of deformation) leads to the coexistence in the material of two types of areas – involved and not involved in the deformation process [Рыбин, 1986].

One of the most important directions in the studies of the processes of plastic deformation is the determination of the marginal formability. Two approaches are applied for this purpose, based respectively on the plastic resource and the loss of sustainability of the deformation process. The former one determines the marginal formability by the disruption ensuing as a result of the depletion of the resource in terms of a given mechanical deformation scheme. In the latter approach the formability is limited by certain criteria for the loss of stability of the process and the associated localisation of the deformation.

There are two known macroscopic manifestations of the localisation mechanism after the loss of sustainability of the deformation process, in which the previously steady deformation localises in a given area. Accordingly, there is an initial scattered (diffused) deformation, followed by a concentrated local deformation. It is assumed [Hora, 2003] that the type of the localisation depends on the nature of the deformation state (as defined by the parameter of the deformation state $\beta = \varepsilon 1 / \varepsilon 2$, $\varepsilon 1 > \varepsilon 2$): in the range of $\beta \in [0; +1]$ occurs as scattered deformation, while in the range of $\beta \in [-1; 0]$ occurs as concentrated local deformation.

The approaches for the determination of the moment of the loss of stability are based on different sets of criteria: force criteria; criteria for limiting stress; criteria based on patterns of damage; bifurcation criteria. The classic force criterion for the loss of stability, the maximum force criterion (MFC), is proposed by Swift and is formulated as $dFx = 0$ or $d\sigma 1 / d\varepsilon 1 \geq \sigma 1$, where $\sigma 1$ and $d\varepsilon 1$ are respectively the maximum principal stress and strain [Swift, 1952]. It applies to homogeneous state of stress (constant normal stress and neglected tangential stress) and determines the moment in time of the occurrence of the diffused localisation of the deformation.

The modified force criterion (MMFC) is formulated by Hora and Tong for three-dimensional stress state [Hora, 1994]. It leads to the emergence of an additional effect of hardenability which displaces the start of the localisation to higher values of deformation. The additional hardenability is represented as β and is not assumed as constant, but is included as a variable parameter in the formula that is describing the MMFC:

$$\delta\sigma 1 / \delta\varepsilon 1 + \delta\sigma 1 / \delta\beta \times \delta\beta / \delta\varepsilon 1 \geq \sigma 1 \quad (1)$$

Even more accurate is the enhanced modified force criterion (EMMFC), since its formulation includes not only the additional hardenability, but also takes into account the thickness of the material and the correlated probability for propagation of the crack.

The field of experimental mechanics uses as methods for the measurement of the deformation of solid bodies different variants of the so-called close range photogrammetry – analog, analytical and digital [Zeng, 1992].

In recent times the importance of digital photogrammetry is constantly growing. It records a point on the surface of the object on consistently captured analog or digital images (photographs) with a high resolution camera. Its spatial coordinates can be derived from those of the corresponding points in the plane of the images. The geometric data is subjected, including in real time, to mathematical processing through the use of specialized software [Rastogi, 1999]. Among the distinctive features of digital photogrammetry is the absence of specific mechanical modules, mechanically induced inaccuracies in the measurement and calibration, the geometrically stable storage of data, the possibility for combination of different sensors and the reconciliation of recording, processing, editing, storing and managing of the data in a given system [Ламбин, 1987].

Of increasing importance for the deformation studies are the modern automated systems for optical 3-D analysis based on photogrammetry, which combine into one all the stages of the information process. The optical systems ARAMIS, AutoGrid, ARGUS use photogrammetric algorithms to recognise the positions of the points of intersection of the reference grid placed on the object in space and calculate their movements from their initial positions. The results converted into deformations are presented most often in the form of graphics or 3-D visualizations [Feldmann, 2006; www.gom.com, 2009]. The accuracy of the measurement of the automated systems is dependent on the degree of heterogeneity and the scale of the deformation. The automated optical systems are most effective when seeking maximum data density with minimum base length of measurement. The deterrent for their mass practical application is their high price.

The data processing in photogrammetric methods is most commonly performed through the use of digital images correlation analysis (DIC). The digital (discrete) image represents a matrix of values that correspond to the average integral value of the vicinity around a given discrete point. The correlation methods compare the sequentially recorded images, while the evaluation and the measurement of the deformations are based on the creation of the fields of the vectors of displacement of the individual elementary areas (dots) and the subsequent determination of the components of the deformation [Напрюшкин, 2008]. There are two approaches used for the determination of the marginal formability in terms of the localisation of the deformation: space dependent and time dependent. The various methods differ in the dimensionality of the determined deformations.

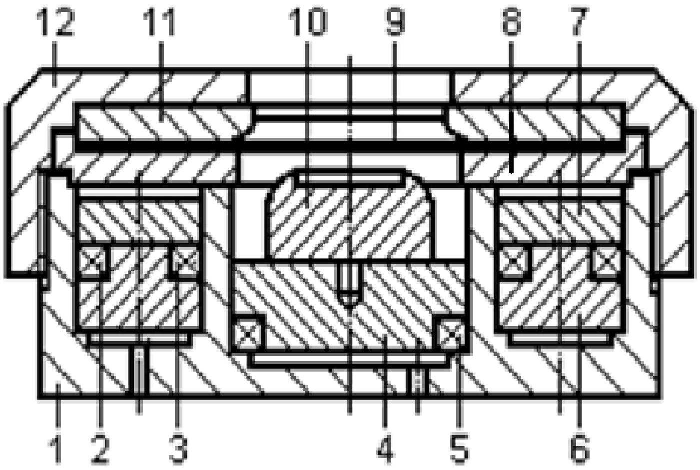
The 0D method is not distinguished with high accuracy. It does not consider the focused localisation and therefore the values of the deformations are adjusted by a factor based on empirical assumptions.

The 1D method determines the marginal formability in pre-selected sections using mathematical criteria. The method is based on the assumption that after the start of the localisation the deformations outside of its area remain constant, allowing the assessment to be carried out just before or just at the time of the occurrence of the crack [ISO/DIS 12004-2, 2008]. One version of the classic sections based method is the time dependent one with its two varieties: gradient and differential. The former takes into account not only the distribution of the deformations, but also the temporal variation of their gradient. An advantage of this method is the ability to automate the calculation procedure [Eberle, 2008]. The differential sections based method determines the moment of the loss of stability on the basis of the temporal variation of the differentials of the main deformations.

The 2D method, unlike the sections based one, depending on the moment in time assesses not a single section, but all of the points from the raster. Based on the global distribution of the coordinates of all the images and under the assumption of an idealised grid, the deformations can be calculated through the function of Lagrange [Volk, 2006].

3. Experimental Procedure

For the testing purposes of the deformability of sheet metal an experimental rig is constructed, consisting of a hydraulic unit, a tool for carrying out the deformation process (Figure 1) and an electronic unit for recording and control. The latter includes a pressure transducer CPT 2500, 0/160 bar with adapter CPA 2500 and software USBRAM DDR2 by the company WIKA Alexander Wiegand GmbH & Co KG. This allows the moment of the loss of stability of the deformation process under the classic force criterion to be determined based on the analysis of the variation in the pressure of the fluid through the specialized software USBsoft 2500.



1 – casing; 2 – sealant; 3 – sealant;
4 – leading unit; 5 – sealant;
6 - element with a T-shaped section;
7 – element with rectangular section;
8 – pressure plate; 9 – specimen;
10 – punch; 11 – matrix; 12 – cover.

Figure 1. Deformation tool.

There is a possibility for the realisation of experiments using the two practically established methods – of Marciniak [Marciniak, 1967] and Nakazima [Nakazima, 1968], and in accordance with the respective punches (cylindrical with flat end or hemispherical) optical schemes with one or two cameras are used for the recording of the optical images. The data obtained through the rig can serve to build MFD – at the occurrence of a visible crack and MSFD – at the occurrence of concentrated macrolocalisation. There is also the option for direct control of the deformation process through the use of additional hardware and software means.

For carrying out the present study an experimental set has been constructed (Figure 2), comprising the aforesaid rig, an intense incoherent light source and a fast digital camera with various lenses and filters.

Figure 2. Experimental set.

The conducted experiments aim to establish the applicability of an optical criterion for the determination of the moment of the occurrence of a concentrated localisation. In line with this task a methodology has been developed, based on the photogrammetric determination of the deformations. Upon juxtaposition of the results with the data recorded under a force criterion for the loss of stability of the deformation process, it is possible to set an empirically established threshold value that determines the emergence of concentrated localisation.

During the experiments series of specimen of sheet metal are deformed at a constant rate, while the stress is discontinued following the final destruction of the specimen. Simultaneous with the start of the deformation process is launched the parallel capturing of sequences of optical images of the surface of the sheet metal in the area of deformation and the registration of the temporal variation of the pressure over the working fluid.

Since the study of formability through the use of coordinate grids is characterised by certain defects leading to a difficult and sometimes subjective assessment of the displacement of the nodes during the deformation process, its use in this case cannot guarantee the accuracy and reproducibility of the results. Therefore another option is preferred in order to quickly and inexpensively obtains the stochastic raster required for the photogrammetry that covers the specified requirements. Following the cleansing of the surface of the specimen it is sprayed uniformly with a coloring agent in the form of an aerosol. The fine colored dots serve to create a unique image in each area. This facilitates the registration of the vector field of the local displacements of a sufficiently large number of points from the area of deformation.

The deformations that correspond to the moment of the loss of stability are determined in three steps: specifying the sections containing the presumed localisation of the deformation; establishing the moment of the occurrence of the focused localisation by means of a criterion set as a threshold value that allows the determination of the internal limitation values for the creation of a distribution curve of the deformation; determining the external limitation values for which for the first time there is a reduction of the curvature of the established distribution.

The setting of the threshold value for the displacement is done in accordance with a suitable force criterion based on the parallel registration of the temporal variation of the pressure over the fluid. In this case the use of the classical criterion for the occurrence of a diffused localisation is justified in view of the precision of the available sensor. The so determined moment of the loss of stability, fixed with some delay following the attainment of the maximum pressure value (allowing its random fluctuations to be neglected), can be considered as the start of the concentrated localisation.

The experiments performed during this study are using the Marciniak method. Round specimen are used with a diameter of 206 mm with bilateral notches with different radius r_m: 0; 43; 53; 60.5; 68; 75.5; 83; 93 mm. Each series of specimen (for a given radius of the bilateral notches) includes specimen with axes of symmetry at 0^0, 45^0 and 90^0 to the direction of rolling. The numbering of the series is in ascending order from the smaller to the larger radii. The specimen tested are comprised of sheet steel 08kp with thickness s = 0.7 mm and indicators: R_e = 190 MPa, R_m = 600 MPa and a coefficient of deformation hardenability n = 0.370.

A camera UI-1490ME with a USB 2.0 interface and a CMOS sensor by the company Aptina with resolution of 10 megapixels (3840x2760) is used for capturing the images. It is fitted on a tripod above the specimen and the image is centered at the specimen. Thus, when capturing a specimen with a size of 200 mm is obtained a resolution of the camera of up to 50 μm. The camera is positioned so that the field of the lens covers the whole area of deformation in the zone of the specimen that is free of stress. For the series from 5 to 8, in which the stress state is of a biaxial tensile, the area of the expected thinning due to the localisation and respectively of the breaking, is at the center of the area of deformation under optimum conditions of deformation or in the vicinity of the radius of curvature under degraded conditions of friction. This requires the registered image to cover the entire observed surface and the capturing is done at a lower speed in order to ensure a sufficiently high resolution of the entire field of the image. Due to the limited bandwidth of the interface and the built-in computing power in the camera, the experiments with the capturing of the entire surface of the specimen are with a maximum speed of 2.5 frames per second. This requires the use of a lower capturing speed in order to ensure a sufficiently high resolution of the entire field of the image. Under a strained state of tension-stress (for series from 1 to 4) the thinning and breaking are expected to occur in the central area of the specimen, which allows for the increase in the speed of capturing to 6 frames per second at the expense of a reduction of the scope of the frames while preserving the image quality. Used is a lens with a depth of focus that is sufficient for operation over the entire range of variation of the distance during the deformation process due to the relative displacement of the surface of the specimen (the image plane).

In order to increase the speed of measurement the amount of data is reduced by capturing only the part of the specimen, in which the localisation of the deformation is expected to occur. For example, for the narrowest specimen (from series 1 and 2) a rectangle encompassing the central region for width and along their whole length is used, in order to determine with sufficient precision the correlation between the deformation in this area and the other areas. The analysis of the results can be based mainly on two orthogonal cross sections passing through the geometric center of the specimen, one of which is parallel to the notches of the specimen, meaning in the direction of the maximum principal stress σ1.

Software has been developed for the mathematical processing of the results based on the correlation analysis of the optical images using the classical and the gradient sections based methods. For the calculation of the deformation the displacement of the points from the raster over the entire surface of the specimen is monitored.

Pretreatment is performed following the registration of the input image in order to correct the distortions of the input converters. Digital filtering is then used in order to eliminate the impact of the changes in lighting. This is followed by a reduction of the information in order to reach a compressed representation comprising only of the essential features for the processing.

The algorithm performs segmentation of the discretisation grid by dividing it in correlation subareas. In order to ensure the successful processing of the results of the photogrammetric measurements through correlation analysis it is necessary that every correlation subarea has a unique image, provided in this case by the fine raster structure of colored dots. The achievement of high resolution requires good autocorrelation coefficients for the correlation subareas over the entire observed surface. A size for the subareas of 64x64 pixels is selected for this case as a compromise between the requirement for greater measurement accuracy and the reasonable computational time. This results in the stable detection of the correlation maximums at a good resolution for the grid of correlation subareas. Their number is 60 along the length of the specimen and ranges from 16 to 43 through their width.

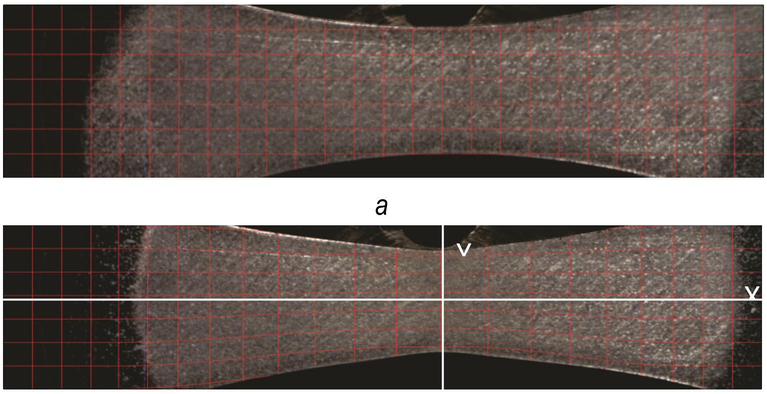
The processing of the results is performed through the use of a standard correlation formula of the type:

$$C_{fg}(u,v) = \frac{1}{N}\sum\sum f(i,j)g^{*}(i+u, j+v) \qquad (2)$$

In which the functions f and g are the values of the intensity of the halftone images of the sought pattern and the deformed area in which said pattern is sought; u and v are the respective displacements along the axes X and Y; * is a complex conjugate of the argument; N is the amount of pixels; i and j are indices of summation.

The binarization enhances the correlation maximum and increases the area in which it can be found with an increase in the deformation.

The correlation subareas in the area of deformation, as well as the abovementioned main sections, are shown in Figure 3.



a

b

Figure 3. Correlation subareas on the specimen: a) in undeformed state;

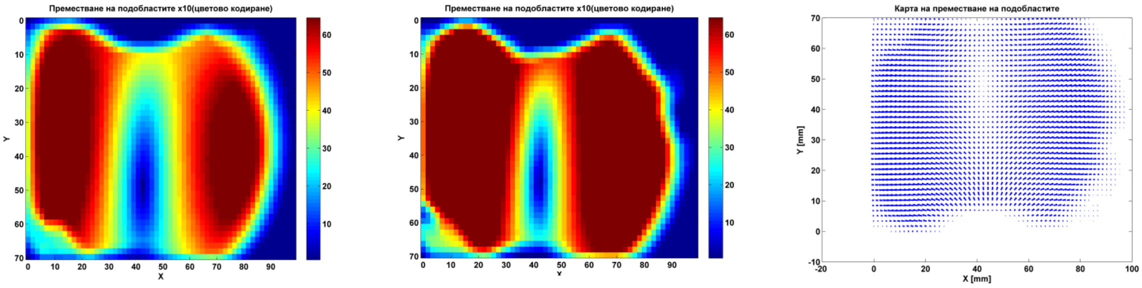
b) immediately prior to breaking following the emergence of a concentrated localization.

4. Results and discussion

The following figures contain some of the possibilities for the visualisation of the data obtained from the testing of the specimen from series 4 with longitudinal axis at an angle of 0^0 towards the direction of rolling – color distributions graphics, vector fields, distribution curves for sections.

Shown below are the results from two characteristic moments in time from the deformation process: following the emergence of a concentrated localisation and immediately prior to breaking. The data for the moment of breaking, uniquely determined by the distortion of the image plane, is taken from the last valid frame. Reverse temporal synchronisation is performed between the captured series of optical images and the registered data on the temporal variation of the pressure. Based on the analysis of the results of preliminary experiments is established a threshold value to define the moment of the loss of stability. It is established that a pressure drop of 0.01 MPa after it has reached the maximum on the curve of its temporal variation eliminates its random fluctuations to the order of 0.005-0.007 MPa and provides adequate reproducibility of the results.

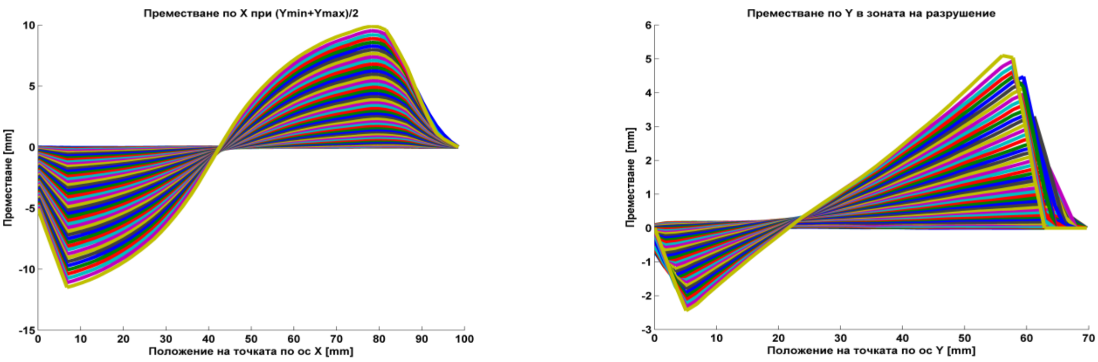
Figure 4 shows X-Y-cards of the displacement of the correlation subareas. The area with minimal displacements can be distinguished, in which later forms the area of focused localisation. It is evident, that its location remains unchanged over time, while in the surrounding areas the displacements increase with the distance from it and in the course of the deformation process.



a *b* *c*

Figure 4. X-Y-maps: displacement of the correlation subareas in color code at the moment of the loss of stability (a) and immediately prior to breaking (b) and the vector fields of the displacements (c).

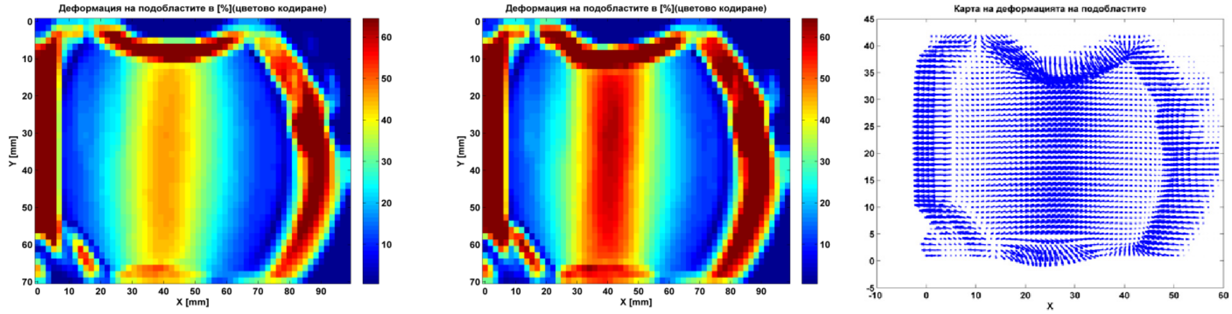
The distribution curves of the displacements along the axes X (a) and Y (b) are shown in Figure 5.



a *b*

Figure 5. Displacement along the axes X (a) and Y (b) immediately prior to breaking.

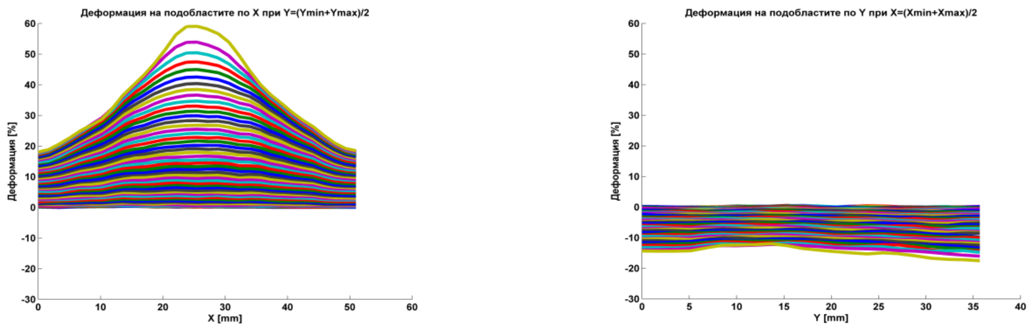
The following figures show in graphical form the deformations in the correlation subareas marked in Figure 3, calculated using specialised software. The presented X-Y-cards reveal (Figure 6) that the location of the area of the localisation remains unchanged until the moment of breaking, while the deformation within it is gradually increasing with the attenuation of the process of plastic flow in the other areas. This is clearly illustrated by the vector field of the deformations from the last valid frame before the breaking, in which the area of localisation is clearly outlined (Figure 6c).



a *b* *c*

Figure 6. X-Y-maps: the deformations of the correlation subareas in color code at the moment of the loss of stability (a) and immediately prior to breaking (b) and the vector field of the deformations (c).

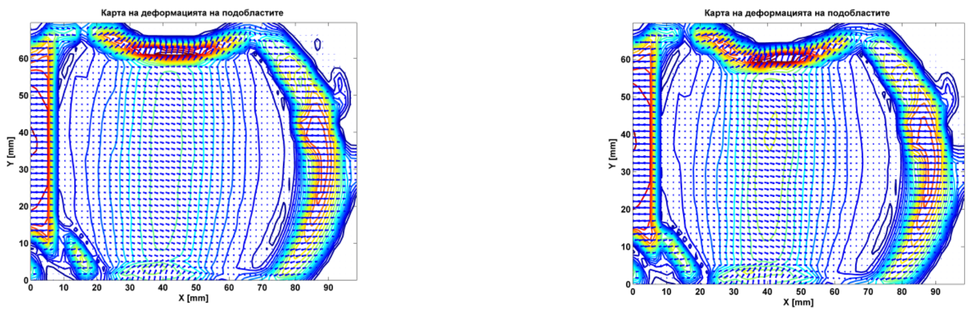
The distribution curves of the deformations along the axes X and Y, shown in the following Figure 7, confirm those observations.



a *b*

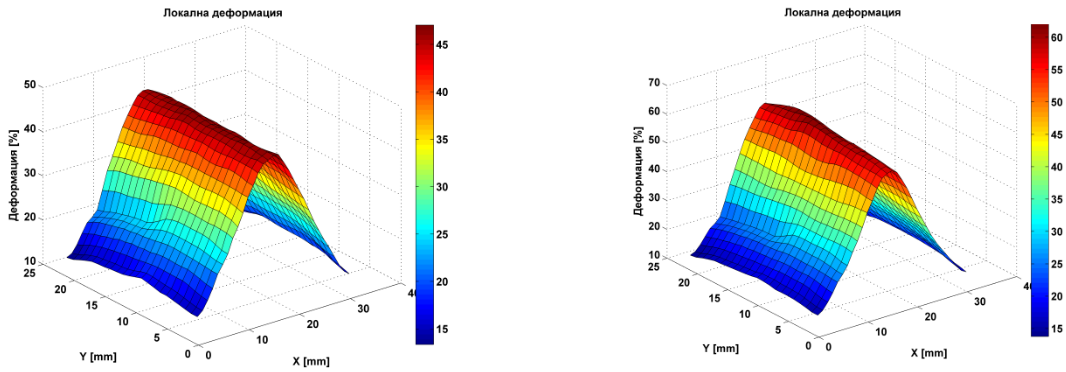
Figure 7. Distribution curves of the deformations.

Figure 8 shows the X-Y-cards of the grid with isolines and vectors of deformation, while Figure 9 shows the three-dimensional deformations in color code at the moment of the loss of stability and immediately prior to breaking throughout the entire observed surface of the specimen. These graphs reveal the most accurate presentation of the location and the shape of the area of the concentrated localization.



a *b*

Figure 8. X-Y-cards of the grid with isolines and vectors of deformation at the moment of the loss of stability (a) and immediately prior to breaking (b).



a *b*

Figure 9. X-Y-maps of the three-dimensional distribution of the deformations in color code at the moment of the loss of stability (a) and immediately prior to breaking (b).

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