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DETECTION OF DEFECTS IN BULGING PROCESSES BY MEANS OF DYNAMIC LASER SPECKLE

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Abstract

The method described in this paper has been used to determine the moment when defects appear in the form of strain localization and grooves in the Marciniak bulging tests. In this method based on dynamic laser speckle, the sheet is illuminated by laser. Interference after reflection from the specimen surface creates a characteristic image of bright and dark spots. Specimen surface changes related with deformations and movements cause changes in the shape and size of spots, which are presented by authors in the form of speckle activity image. In order to identify the type of defect, the additional 3D microscopy measurements were performed. This paper presents analysis of the changes in the speckle activity image during the bulging process which enabled the defects identification during the bulging process.

Key words: sheet metal, bulging, Marciniak test, vision system, laser speckle, 3D digital microscope

1. INTRODUCTION

Metal stamping is one of the most common metal forming processes. This process is limited by defects in the form of grooves and cracks formed after exceeding the limit values of the deformation. The ability to precisely determine the onset of groove appearance helps to avoid the occurrence of defects in the bulging process. There are formability tests applied in order to determine the forming limit strain associated to defects formation. Strain measurement is one of the method used in the sheets forming limit determination. This method usually used coordination grids applied to the surfaces of the sample (Shi & Liang, 2012; Turkoz et al., 2010). Beyond this method strain localization can be also detect by means of hybrid method based on the experimental and simulated bulging load (Galpin et al., 2016) or using ESPI (Electronic Speckle Pattern Interferometry). ESPI allows to detect the strain localization by means of unique fringe pattern occurring on the sample surface where the strain localization takes place (Wang & Liu, 2010; Guelorget et al., 2006). Furthermore, there are methods allow to detect the strain localization based on analysis of heat sources distribution on the sample surface (Dumoulin, 2010). In another method defects could be detected by means of magnetic field measurement occurring around a ferromagnetic material (Zimniak & Hankiewicz, 2006). Increasingly, formability tests are accompanied by advanced methods of image analysis allowing material deformation measurements and defects detections. In this paper authors present a new method for defects detections, based on dynamic laser speckle activity analysis. This method doesn't require any grids application or special surface preparation, because it is independent of the strain measurement. It could be easy applied to any type of sheet metal. Presented method is based on vision measurements therefore examined surface must be visible during all the process. For defects

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detections is necessary to record speckle activity during all the process.

For verification detected defects were also measured by means of 3D digital microscope in order to verify results obtain by laser speckle method.

2. DYNAMIC LASER SPECKLE AND SPECKLE ACTIVITY IMAGE

In the presented studies a dynamic laser speckle phenomenon was used (Rabal & Braga, 2009) for detection of the moment of strain localization and grooves occurrence during the bulging process of sheet metal. Recorded laser speckle images were analyzed with Digital Image Correlation, whereby information was obtained about the time and the location of forming defects.

2.1. Laser speckle phenomenon

Coherent light waves, leaving the source, which may be eg. a laser, are being characterized by the same length, phase and amplitude. Due to the interference, coherent light creates the time-invariant areas of strengthening and weakening of the light. As a result of reflection of the coherent light beam from a rough object, a shift in phase of each wave takes place (figure 1a). The reflected beam, incident on the image plane, creates a characteristic interference pattern called laser speckle (figure 1c).

Laser speckle may be recorded for static objects and objects showing various types of "activity". The tested object may be subjected to changes such as movement, deformation, the orientation change or the different kinds of biological activity. In this case, recorded laser speckle undergo dynamic change (dynamic laser speckle). Dynamic laser speckle may be registered continuously, allowing not only to track global changes such as displacement of the surface, but also allows to detect differences in the activity of the individual areas of the tested object. This phenomenon has many applications, one of them allows detection of strain localization in the Erichsen cupping test (Kocańda & Jasinski, 2016; Kocańda & Jasinski, 2014). Speckles on dynamically registered images may change shape and position, may also appear and disappear. Often speckle activity, connected with changes on the registered surface resembles boiling water (Rabal & Braga, 2009).

2.2. Speckle activity image

There are many methods of analyzing the distribution of laser speckle activity on the surface of the tested object. These are inter alia differential images, the method of testing the contrast or a time history of speckle pattern (THSP). In order to analyze the dynamic laser speckle used in the research presented in this paper, the authors used to visualize the degree of correlation of the sequentially registered laser speckle images. This task was carried out with the help of the correlation function

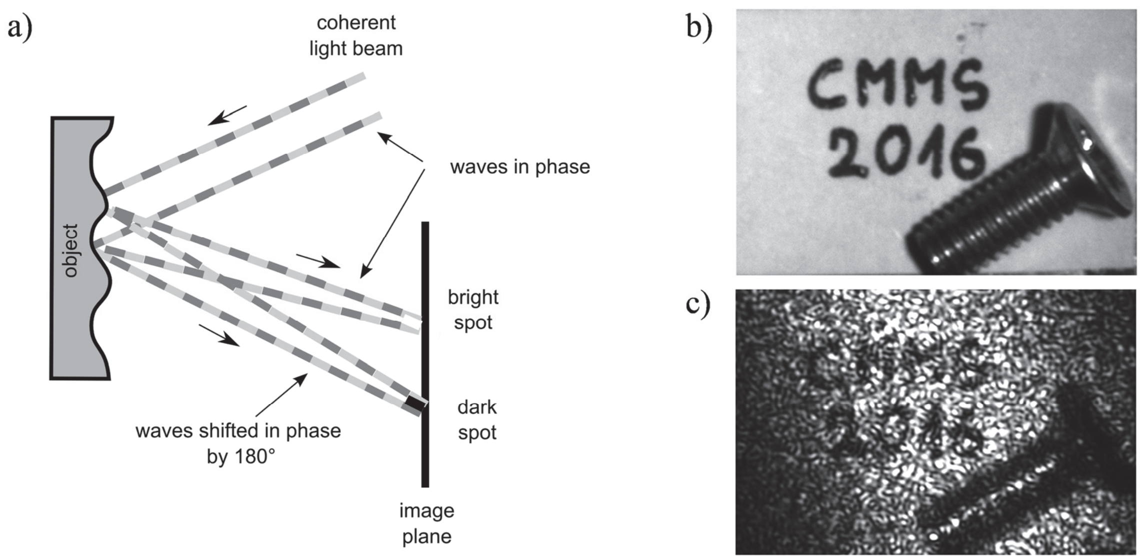

Fig. 1. The principle of laser speckle occurrence (a) (Jasiński et al., 2015), example of illuminating the objects with incoherent light (b) and coherent light (c)

(equation 1), which allows to determine the degree of similarity C of the two images (Relf, 2004):

$$C = \frac{\sum_{x,y}(T1_{xy}T2_{xy})}{\sqrt{\sum_{x,y}T1_{xy}^2 \cdot \sum_{x,y}T2_{xy}^2}} \qquad (1)$$

where C is the correlation coefficient, $T1_{xy}$ and $T2_{xy}$ describe pixels gray levels on the images 1 and 2 in points with coordinates (x,y).

Correlation coefficient C takes maximum values for identical images, and minimum for completely different ones. Registered laser speckle (figure 2a, b) were divided into small areas (10x10 pixels). For each of these areas registered in subsequent images (figure 2a, b) the laser speckle activity was visualized where given value C was specified by pixels gray level on the initial image. This made it possible to detect places where the strain localization takes place. The places with a higher activity (lower correlation coefficient C) were marked as brighter on the images of speckle activity, while the places showing a smaller degree of change (higher correlation coefficient C) were marked with a dark color (figure 2c). The speckle activity images performed this way are referred to an acronym OAP in this paper.

3. MARCINIAK DRAWING TEST WITH AN EXPERIMENTAL VISUAL STAND

The sheet metal Marciniak bulging test was used in this study. This method is mainly used in determining the forming limit diagrams and it allows to obtain various strain states in the tested sheet metal. Steel samples DC04 with assisting rollers, used in Marciniak test, were deformed by using an universal Erichsen hydraulic device with a stamp having a diameter of 33 mm. The bulging process was registered by using a specially prepared video system. This system enabled the measurement of deformation with a usage of Digital Image Correlation (DIC) and the detection of occurring defects with dynamic laser speckle phenomenon.

3.1. Measurement stand

Sheet metal bulging tests were conducted on a universal Erichsen hydraulic device. The device was equipped with a specially designed punch and die to carry out tests while using the Marciniak method. The construction of the device head, wherein the die is attached to, enabled the registration of

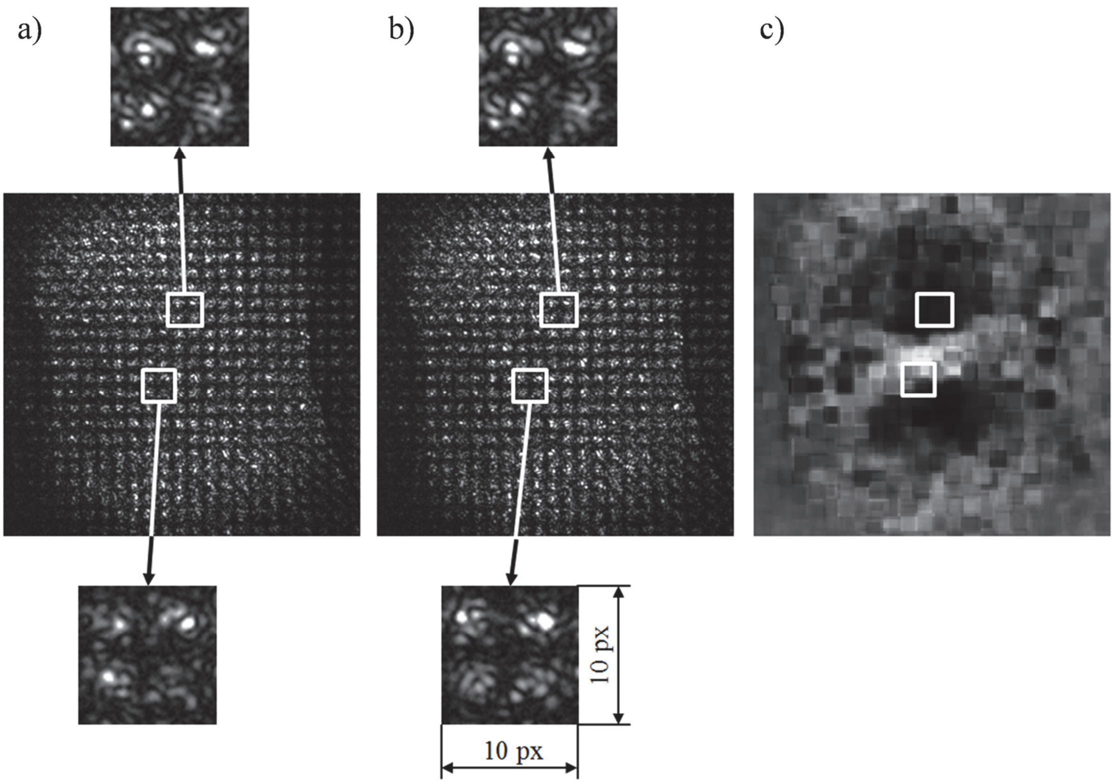

Fig. 2. Successive laser speckle (a, b) and the resulting speckle activity image OAP (c)

the surface condition of the tested samples during the process with the usage of the vision system. The basic elements of this system are: a CCD camera, camera lens with a focal length of 35 mm, laser illuminator with a power of 7 mW and a wavelength of 655 nm, LED illuminator emitting a green light, triggering device and a PC computer designed for recording the images registered by the camera. The scheme of the vision system is shown in figure 3.

of the speckle activity in different areas of specimens was conducted.

3.2. Conducted studies

An adequate surface preparation of the samples was required for the strain measurement while using DIC. It was decided, in these measurements, to use the stochastic pattern. Grids of this type, in comparison to grids with regular pattern may be quickly and easily applied to the surface of the sheet metal and tracing the displacements of such grid does not create problems while using DIC. A red aerosol spray paint was used for the application of the stochastic grid onto sheet metal surface. Choosing the red color of the grid allow to limit its influence on the measurements using a red laser (655 nm). In the presented studies, DC04 steel samples were used of 0.8 mm in thickness, figure 4.

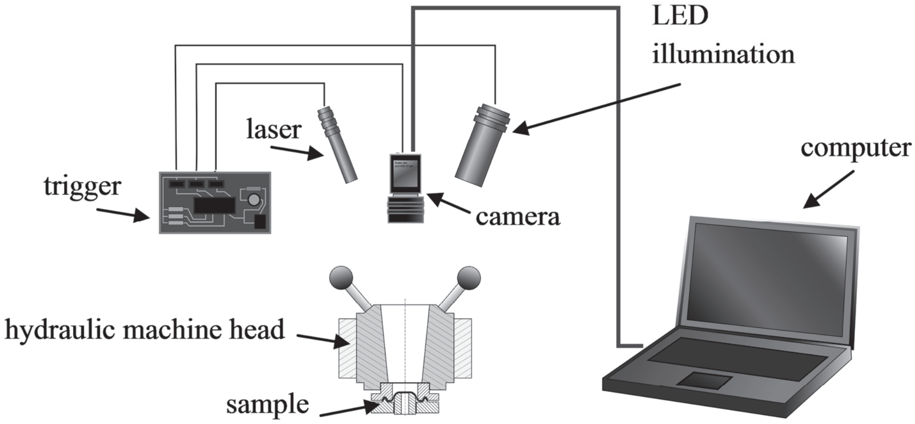

Fig. 3. *Scheme of the measurement setup*

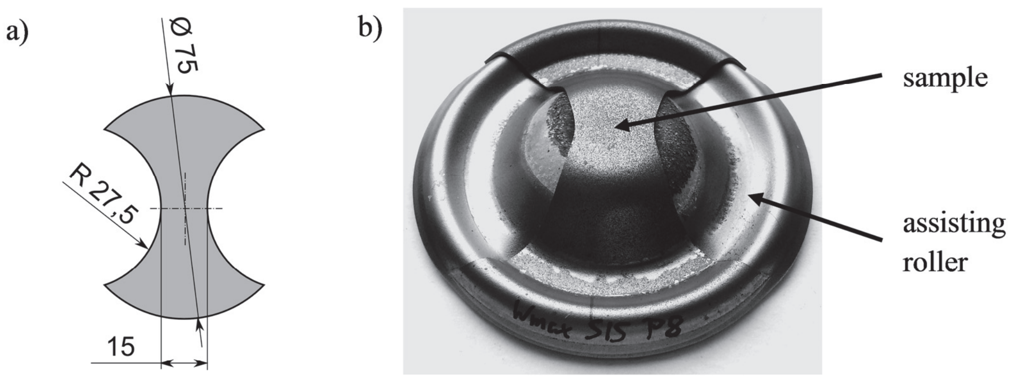

Fig. 4. *Dimensions of the samples used in this study (a) and the sample after the bulging process with a visible stochastic grid, placed on the assisting roller (b)*

During the registration of the bulging process by vision system, samples were alternately illuminated by the LED illuminator and the laser. A specific triggering device was used for the synchronization of lighting and camera. Vision images registered for LED lighting were used to measure the deformation of the sample surface (Jasiński, 2015). This task was accomplished with a proprietary software using Digital Image Correlation technique. Images registered with a laser light made it possible to generate speckle images activity (OAP), under which the analysis

During the conducted studies, samples having different degrees of deformation were obtained (figure 5b), when deformation was stopped at various characteristic steps of the process, i.e. uniform strain phase, strain localization and formation of the groove. Figure 5a presents measured strain with a use of the vision system (Jasinski, 2015).

4. 3D RECONSTRUCTION OF THE SURFACE

All samples were tested on 3D digital microscope (figure 6b) in order to know the geometry of the occurring defects during the bulging process. The measurement method used on the microscopic stand is based on a very shallow depth of sharpness

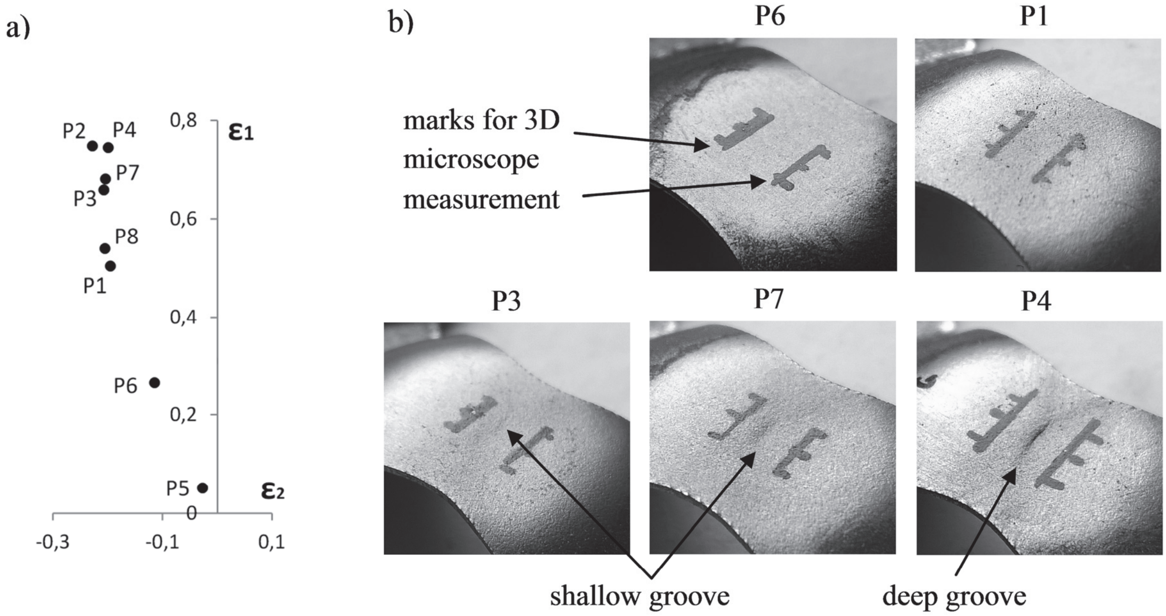

Fig. 5. Level of deformation (a) and exemplary images of the surface (b) of the tested samples with numbers from P1 to P8

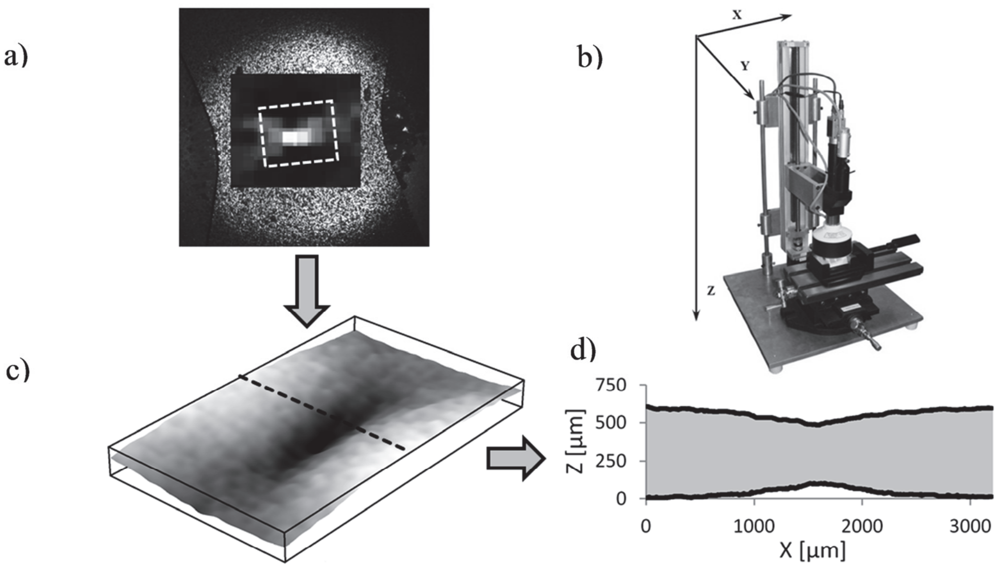

Fig. 6. The area of the sample subjected to measurement of 3D geometry (a) on the microscopic stand (b) (Morawiński & Kocańda, 2015) and the obtained 3D geometry (c) and the sheet metal cross section (d)

(Morawiński, 2015; Morawiński et al., 2013), thanks to which the tested surface area (marked with a dashed line in figure 6a) is visible only in a narrow range of distances from the optical system. Changing these distances can create a depth map on the basis of which the 3D geometry of the surface of the object is obtained (figure 6c).

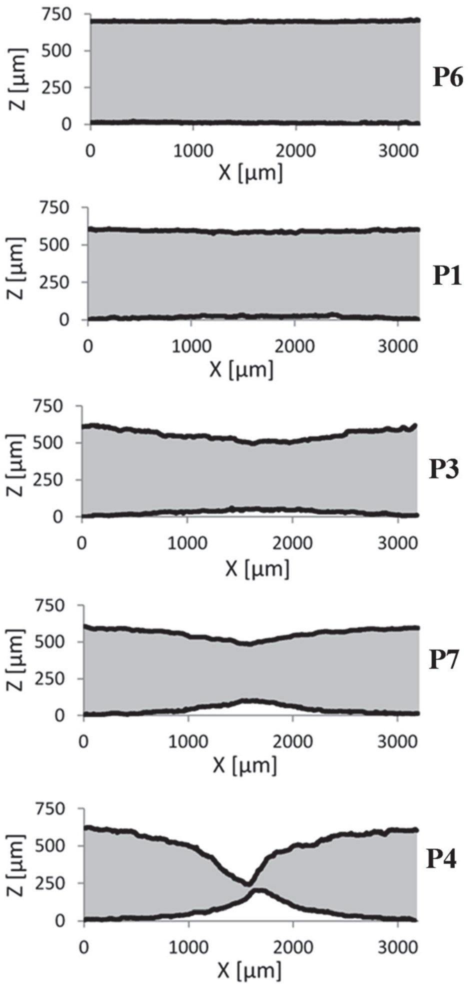

Fig. 7. Exemplary cross-sections of the samples obtained from microscopic measurements

Figure 6a shows OAP overlaid on the surface of the sample P7. The white dotted line indicates the samples area studied on the microscope stand. 3D geometry of the surface of the bulged sample was obtained from the 3D digital microscope. Then based on 3D surface geometry, 2D geometry in form of outlines has been obtained. These outlines ran in the direction of the largest deformations, at the defect location. The measurements were made on the top and bottom surface of the bulged samples. Knowledge of the upper and lower outline of the 2D surface geometry and thickness of the samples obtained by measurements with dial indicator made it possible to generate a 2D geometry of the sample cross-section (figure 6d). Figure 7 presents the 2D geometry of the measured samples. DC04 sheet thickness before the process was 0.8 mm. P6 sample thickness was reduced from 0.8 mm to 0.7 mm on the whole measurement area, which indicates a uniform deformation of the material. Sample P1 has slight differences in the thickness of the material, which prove the strain localization start to occur. The thickness of the sample at the periphery of the measuring area is 0.6 mm, while in the central part of the cross-section drops to 0.55 mm. The cross-section of the sample P3 indicates the location of a further expansion of the deformation, whereby the thickness of the sample at the location of groove has fallen to 0.45 mm. An emerging groove can already be seen in the sample P7. Sheet metal thickness at this point was 0.39 mm. Another sample no. P4 shows the 2D geometry of the groove just before the crack. The thickness of the sheet at this point decreased to 0.04 mm.

5. SUMMARY OF MICROSCOPIC MEASUREMENT AND ANALYSIS OF OAP

2D sections illustrate the process of changes in the geometry of the samples. As it was mentioned in Chapter 2, the analysis of speckle activity can detect changes occurring on the surface of the sheet metal. In general, this activity is the greater the higher the changes occur in the given area.

Speckle activity depends on many factors such as: a small change in speed of the process, or a local change in the geometry of the surface being caused by the strain localization. For this reason, it is necessary to determine the difference between speckle activity C in the area of defect and the value of C for the adjacent area, being outside the area of defect's occurrence.

Thereby, the results of the analysis are solely dependent on the local geometry change. Figure 8a shows a change in speckle activity C_1, C_2 as a function of the equivalent strain, measured by vision system, for two areas A_1, A_2 indicated in figure 8c. Changes in speckle activity C_1 from the area A_1 are described by dotted line, and the C_2 from the area A_2 is described by solid line. In figure 8a there are three zones indicated on the chart. Increase in speckle activity in zone 1 is due to the initial change in the geometry of the sample which is connected with the mapping of the geometry of the stamp sheet. During

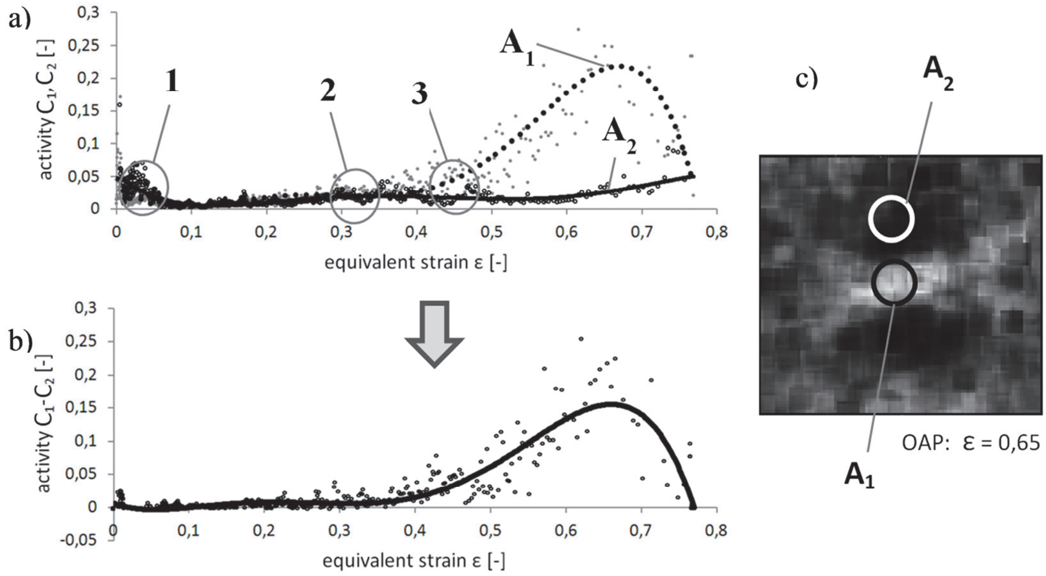

Fig. 8. The speckle activity in area A_1 and A_2 (a), activity difference C_1-C_2 for area A_1 and A_2 (b) and laser speckle activity image of the specimen surface (OAP) (c)

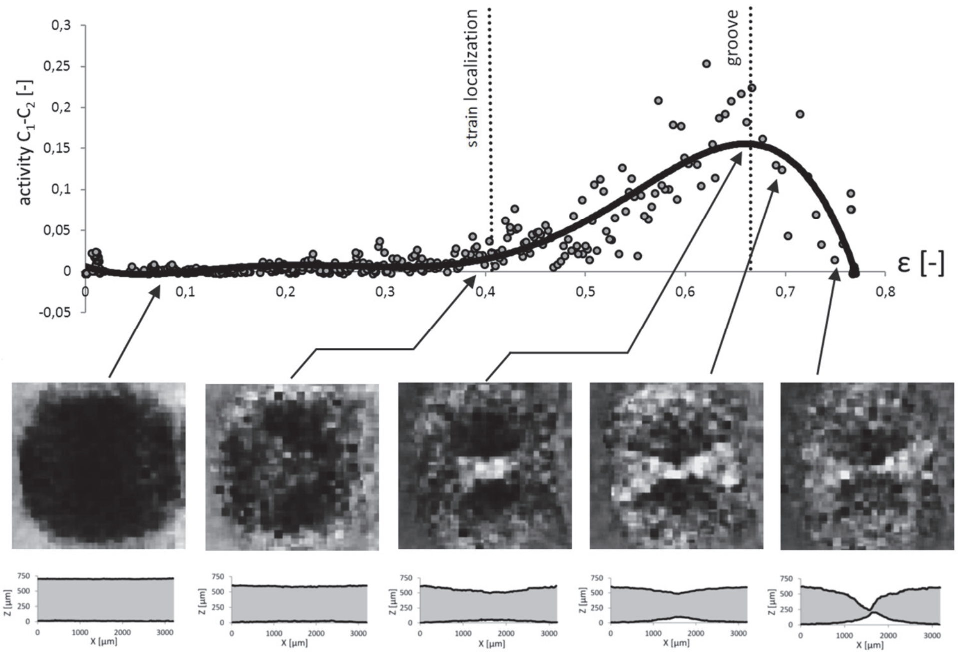

Fig. 9. Changes of speckle activity differences of the groove area connected with OAP and cross-sections of the samples

the process, there were small changes occurring in speed of the punch movement, resulting in changes in the speckle activity value in the zone 2. Differences in speckle activity between the area A_1 and A_2 (figure 8b) are approximately equal to 0 until the moment of the process indicated as zone 3. In this zone a sudden increase in activity occurs, which is due to strain localization arising in the area A_1. The value of the speckle activity differences C_1-C_2 increases until it reaches the maximum value, after which the groove is initiated in place of strain localization.

Figure 9 shows a speckle activity differences in function of the equivalent strain. The arrows indicate the characteristic process steps of the bulging process connected with OAP and the corresponding cross-sections of samples at the place of an occurring defect. A slight increase in speckle activity differences is being visible at the beginning of the process which is caused by the initial change in the geometry of the surface of the sample related to the material mapping of the tool geometry. In the phase of uniform strain, speckle activity differences are close to zero. At the time of strain localization an increase of this parameter is observed by, until it reaches a maximum value being dependent on various factors, ie. the speed of the process. The decrease in speckle activity differences is related to the creation of grooves on the surface of the bulged sample. Figure 9 indicates, that the analysis of changes in the level of speckle activity differences enables the precise detection of the type and the moment of the defect's occurrence.

6. CONCLUSIONS

- The proposed method based on the laser speckle analysis enables the precise detection of the initial moment of strain localization and grooves.
- Precise measurement of the surface geometry of the bulged samples by means of the microscope enabled the study of thinning of the material in the place of the detected defect. The obtained results being compared with information from laser speckle analysis image showed that strain localization is connected with an increase in activity of laser speckle. The subsequent decrease in the activity of laser spots is related to the emerging of groove.
- OAP analysis enables locating and tracking of the development of all defects appearing on the surface of the sample during the deformation process.
- The presented method using the laser light allows the detection of strain localization in the bulging processes without the need for strain measurement. This has been confirmed by tests presented in this paper.

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DETEKCJA WAD W PROCESACH WYBRZUSZANIA Z WYKORZYSTANIEM OBRAZÓW PLAMKOWYCH

Streszczenie

Przedstawiona w artykule metoda wykorzystuje zmienne obrazy plamkowe do określenia momentu powstania wad w postaci lokalizacji odkształceń oraz bruzd w próbach wybrzuszania metodą Marciniaka. W metodzie tej blacha oświetlana jest światłem laserowym, które w wyniku interferencji po odbiciu od powierzchni próbki tworzy charakterystyczny obraz jasnych i ciemnych plamek. Zmiany powierzchni blachy związane z odkształcaniem i przemieszczaniem powodują zmiany kształtu i wielkości tych plamek, co jest przedstawiane przez autorów w postaci obrazów OAP. W celu identyfikacji rodzaju wady wykonywane były dodatkowe pomiary geometrii, między innymi za pomocą mikroskopu 3D. W niniejszej pracy przedstawiono analizę zmian obrazu aktywności plamek OAP w trakcie procesu wybrzuszania, której celem była identyfikacja powstających wad.

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