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STRAIN MEASUREMENTS IN FREE TUBE HYDROFORMING PROCESS

The paper presents a method of measuring deformations of cylindrical samples on the testing machine for free tube hydroforming experiments. During experiments a sample made of a thin-walled metal tube is expanded by the internal pressure of the working liquid and additionally subjected to axial compression. This results in a considerable circumferential deformation of the tube and its shortening. Analysis of the load cases and their impact on the deformations can be helpful in determining e.g. tube material properties or general limiting conditions in the tube hydroforming process. In connection with the above, the value of deformations and knowledge of their course during experiment has become one of the most important problems related to the issue described above.

Keywords: strain measurement, hydroforming, stereovision

1. Introduction

Tube hydroforming allows the production of light and durable components. Therefore, this technology is particularly popular in the automotive and aerospace industries, where the requirements for the parts being manufactured are very high [1,2]. The hydroforming processes are widely used due to their numerous advantages, but also the limitations in their application should not be forgotten. They mainly concern defects arising during the implementation of this type of processes and the selection of optimal process parameters. Many techniques are used to support design, e.g. numerical and computer methods, but due to the high complexity of hydroforming, there are still no universal laws that allow quick selection of optimal process parameters. A number of research stands have been created for testing tube hydroforming processes, both for studying their specific aspects, and for testing the behaviour of tubes under certain forming condition. Some of the research stands either investigated specific processes of die hydroforming [3-5] or focused on the analysis of material properties in free tube hydroforming test [6-8] In most cases relatively short tube sections were deformed and introduced into a biaxial stretching condition. Thanks to the monitoring of geometry in connection with the knowledge of the process parameters, it was possible to determine the plastic properties of the tested tubes. The deformation measurement itself was carried out using various techniques (non-contact or DIC techniques), but due to their inhomogeneous state, determining the material properties of the tested tubes required complicated calculations, often using finite element method [9,10].

The tube hydroforming measurement site (hereinafter referred to as the TH stand or TH machine), designed and built at Warsaw University of Technology, extends the possibilities of analysing tube hydroforming processes presented so far. It allows both die and free tube hydroforming processes to conduct and therefore, it is possible to obtain information about the material as well as optimal process parameters [11]. On the basis of a number of experiments it was observed that with appropriate process parameters there is a uniform increase of circumferential strain. This means that on the measuring section the tube deforms evenly, and only at the end of the process, a local bulge occurs. The existence of this uniform stage of tube hydroforming and the consequent simplification of the geometrical relations of the deforming tube could facilitate further process analysis, e.g. determining the material properties of a tested tube. To examine phenomena occurring in free tube hydroforming processes, e.g. uniform stage or local bulging, a special system for measuring strain using DIC techniques was designed and built. This article presents the capabilities of the TH stand vision system with the example of selected free tube hydroforming experiments.

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2. Free tube hydroforming test

As mentioned in the introduction, the TH stand allows to conduct tube hydroforming tests using circumferential extension of the tube by working liquid pressure with simultaneous axial compression or stretching. Axial loads are realized by the hydraulic cylinder placed in the axis of the tube, whereas the process of circumferential expansion is achieved due to the high pressure of oil injected into the tube [12].

The main research goal of the TH stand was to analyse the parameters of free tube hydroforming of long tubes in terms of stability loss conditions. The free tube hydroforming test can be an alternative version of the tube bulging test, due to the different strain distribution. The free tube hydroforming test consists in attaching the tube ends to the holders (clamps) and obtaining deformations of tube caused by the working liquid pressure and displacement of the actuator. The features of the station were designated, so that it is possible to obtain variable states of strain and stress in shaped tubes. The appropriately selected test parameters allow the tube be subjected to internal pressure expansion with both axial compression and tension.

The free tube hydroforming test is performed in accordance with a control plan introducing a relationship between the working (internal) pressure p_w and the pressure p_c in the hydraulic cylinder. This dependence can be described by the equation $pc = a \cdot p_w + b$, where p_w and p_c are described pressures then a and b are constant parameters entered into the control panel before test begins. The control program shows that increasing the pressure p_w, the p_c pressure in the hydraulic cylinder also increases. The axial force F is dependent – on the one hand – on the hydraulic cylinder pressure, and – on the other hand – on the resistance of the formed tube. Depending on the values a and b it is possible to form the tubes by creating a wide range of stress and strain in the tube wall. During the tests at the TH stand it is possible to record data from several sensors: pressure transmitters for working and cylinder pressure, load cell for axial force and distance sensor for the cylinder piston movement. These data enable a later detailed analysis, in order to examine their impact on tube deformation. Numerous free hydroforming experiments were conducted, using various materials and tube geometries [13]. Due to the universal control system, many attempts were made to shape long tubes sections obtaining the uniform deformation phase, in which the measuring section experiences a uniform increase in both peripheral and axial deformations. To control the shape of deformed tubes in previous experiments, a basic registration system was used. It was based on a single camera recording a simple mesh printed on a tube wall [12]. However, using the variable values of parameters a and b the measurements made in this way allowed to clearly observe the phase of uniform deformations (uniform deformation stage).

The existence of uniform deformation stage in the free tube hydroforming can be observed in the experimental case of the steel tube with dimensions of $\phi 48 \times 2$ formed with parameters $a = 0.2$ and $b = 10$. On the basis of the recorded data of the experiment, the process of tube expansion could be divided into several characteristic stages, the first of which (elastic strain stage – E), associated with a sharp increase of internal pressure pw caused elastic deformation of the tube, Fig. 1.

After exceeding the pressure limit, the tube begins to deform plastically in uniform way, i.e. increasing its diameter over the entire measuring section, referred to phases U1, U2, U3 in Fig. 1a. Then, with the internal pressure increasing to the maximum value, the tube goes into an unstable state (N), which is visible in the form of a local bulging of the tube wall. The final stage of the free tube hydroforming is a fracture and it ends the experiment. Thanks to the data registration system it was possible to record process parameters and analyse each of them in relation to the above mentioned stages of the process. An interesting example of such analysis is the connection of the process stages with the internal pressure p_w. The internal pressure p_w diagram for the case described above, was shown in Fig. 1b.

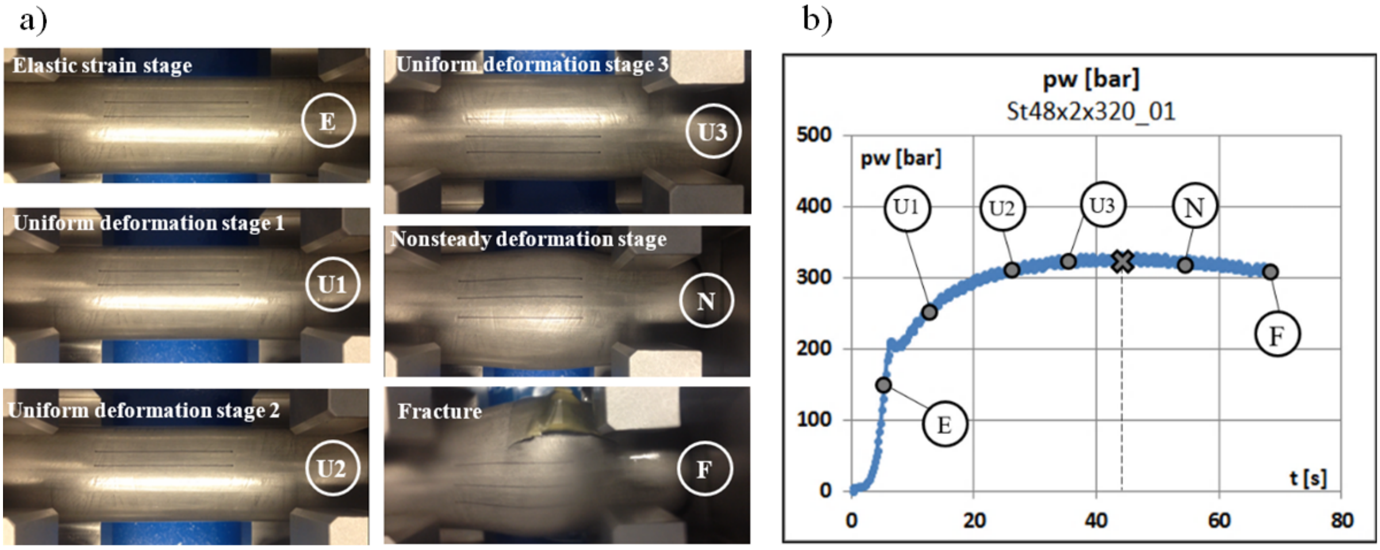


Fig. 1. Free tube hydroforming process steel tube: a) process stages, b) internal pressure pw (history diagram in free tube hydroforming process with $a = 0.2$ and $b = 10$)

Particularly remarkable is the evolution between the U3 uniform stage and the unstable stage *N*, which is associated with obtaining the maximum value of the internal pressure pw. Observing subsequent experiments for different steel tubes, a strict influence of parameters *a* and *b* on the moment of maximum pressure was observed. It was noticed that the increase of both parameters *a* and *b* delays the achievement of the maximum internal pressure connected with the change to the unstable stage of forming. With regard to the performed free tube hydroforming experiments there is a need to verify the proposed division into phases. Such verification could be best performed by analysing the deformations of the tube measuring section. Due to the nature of the free tube hydroforming test and access to the deformed section it is possible to observe the tube deformation during experiment. The confirmation of the uniform deformation phase occurrence requires a special registering system on a relatively long section of the tube. Taking into account the features of the TH machine and test conditions the most appropriate one seems to be a vision system registering the tube geometry in 3D. As mentioned in the introduction there are many ways to register deformations in research trials related to tube hydroforming processes. The most interesting, however, is the vision system that allows the analysis of the entire measurement section as was presented in [14]. Using this concept the TH station was equipped with an unique stereovision system and its construction and exemplary measurements.

3. Strain measurement system for TH testing machine

The TH stand is characterized by certain features that impose the construction of the vision system and the way of measuring performed with it. The elements of the vision system must not stay under the polycarbonate safe screen due to unfavourable conditions occurring during shaping tests, because of the frequent tube wall cracks and a sudden high pressure leakage of the working liquid. This would not only result in mechanical damage to the vision system components but its components would have to be resistant to contact with the working fluid, (machine oil) as well. Favourite features of the station, however, are that the working zone is protected by a movable cover made of durable, transparent polycarbonate, which allows registration of deformation of the tube using a vision system placed outside.

The strain measurements using stereovision are popular and well known from many publications and commercial applications. Stereovision belongs to the group of contactless methods for 3D measurement using vision techniques [15,16]. Geometry measurements using this method are based on the determination of differences in the position of the object points registered on both images. In order to increase the accuracy of the measurement of stereovision geometry, a projector illuminating the object with structural light is often added to the camera system [17,18]. An example of a commercial solution for such measuring system can be the ATOS system [19]. The ARAMIS-type systems also

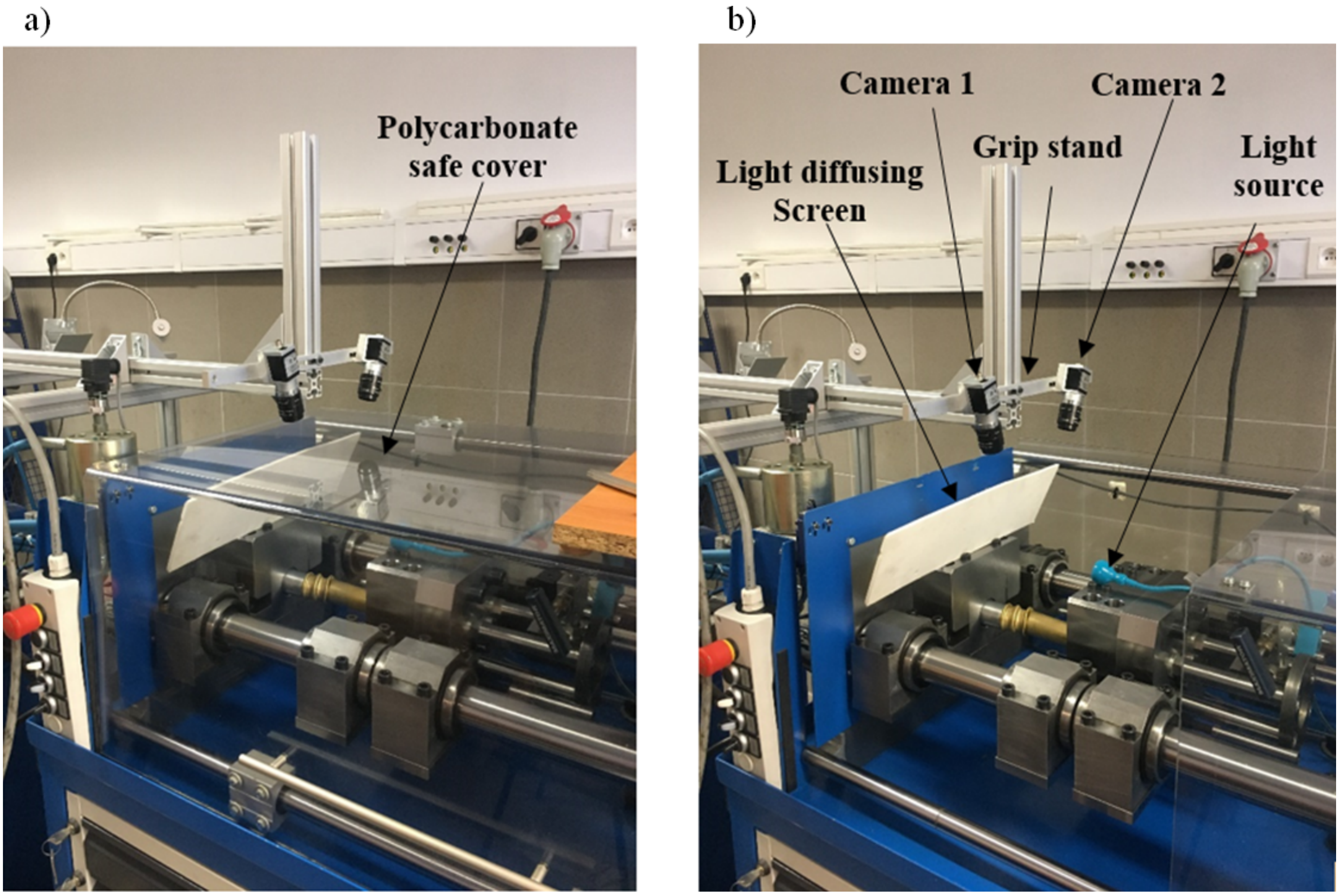


Fig. 2. TH machine work space and stereovision system: a) with closed polycarbonate screen, b) with opened polycarbonate safe screen

belong to the group of stereovision [20]. These are non-contact measurement systems out of plane deformation based on Digital Image Correlation (DIC) [21].

The commercial stereovision systems have many advantages, but they are usually closed and it is difficult to adapt them to the changing conditions of measurement, not to mention their high price. The above reasons, combined with the authors' extensive experience in the field of image analysis, encouraged them to build their own vision system. The characteristics of the created stereovision system allow not only to adapt it to the difficult measurement conditions at the TH machine, but also enables the implementation of necessary changes in its software and equipment. The main purpose of this article was to present technical aspects of deformation measurement of the own prototype stereovision system in relation to specific conditions of free tube hydroforming specific conditions on TH stand and verification of measurement results.

The prototype vision system is equipped with common recording parts: two cameras, illumination, a diffusing light screen, (Fig. 2) and a special software dedicated to geometry reconstruction and deformation analysis. The cameras are placed on a special grip holder located above the work space of the TH stand, (Fig. 2b). For the uniform illumination of tubular specimen a single light source was used and dispersed by a special diffusing screen. The measurements involved the use of two Basler Ace monochrome cameras with a resolution of 1628×1236 pixels with a spacing of at 130 mm from each other equipped with 25 mm focal length lenses. The cameras recorded samples from a distance of about 300 mm. Registration of dynamically changing curved surfaces connected with two basic limitations. The first is the need to use the shortest possible exposure time to avoid blurring the image of the moving object. This blur causes the loss of accuracy and interferes tracing the surface points of the sample. The second limitation is related to the depth of focus of recorded images. For small distances between the cameras and the subject it is difficult to obtain a sufficiently large depth of focus. The depth can be expanded by reducing the aperture. However, this treatment has a negative effect on the amount of light reaching the sensors of photosensitive cameras (and thus longer exposure times are required). These limitations can be optimized by using appropriately strong illuminators and increasing the signal gain on the photosensitive sensor. Finally, the authors decided to use an aperture of $F/10$. This allowed to achieve the depth of focus of about 15 mm. It was a sufficient value for the hydroformed tubes conditions.There were a number of experiments conducted to confirm the accuracy of geometry measurement of tubular specimens placed under the polycarbonate safe screen. Despite the change in the angle of refraction caused by the screen, no significant effect on the geometry results was observed.

The stereovision measurements are based on the determination of pattern points location and are obtained from the images recorded by both cameras. Accurate determination of their position, as well as conversion to 3D coordinates, requires a suitable system calibration. To calibrate the vision system used at the TH stand, a digital calibration pattern generated on a high-resolution screen with a diagonal of 6" was used. The positions of the digital calibration pattern in the measuring zone of the TH stand are shown in Fig. 3. The digital calibration patterns have many advantages over their traditional ones. First, it is possible to generate them with various parameters and then they can be displayed on any screen with high pixel density, e.g. 800 ppi. In addition, the digital pattern is a source of light itself, so it is does not need to illuminate it during calibration process.

To create a reference for the stereovision system a speckle pattern was applied to the test samples, Fig. 4a. This type of pattern has a form of a disordered texture and can be applied using e.g. spray paint. The speckle pattern obtained that way creates a texture on the surface of the sample that allows geometry and strain measurements during the hydroforming process, Fig. 4b.

The search for interdependent points on both images is executed using a normalized cross-correlation. Correlation allows to find an object in the image that corresponds to a specific template. The templates are taken from the image recorded from the left camera and their equivalents are searched on the image from the right one.

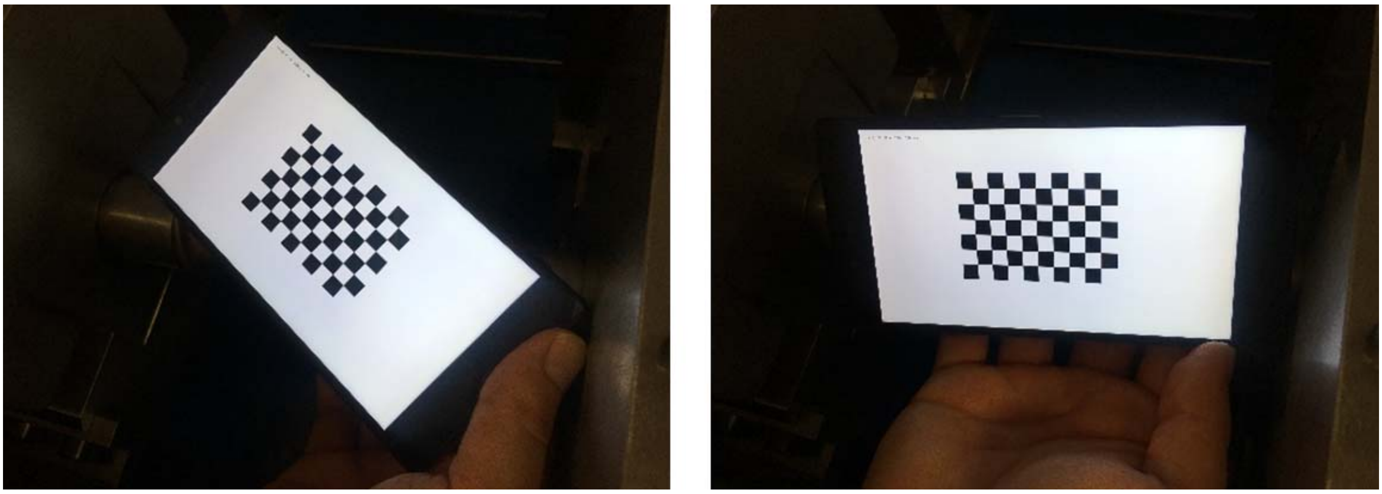


Fig. 3. A digital calibration pattern generated on a high resolution screen in the TH work zone stand for two different 3D space orientations

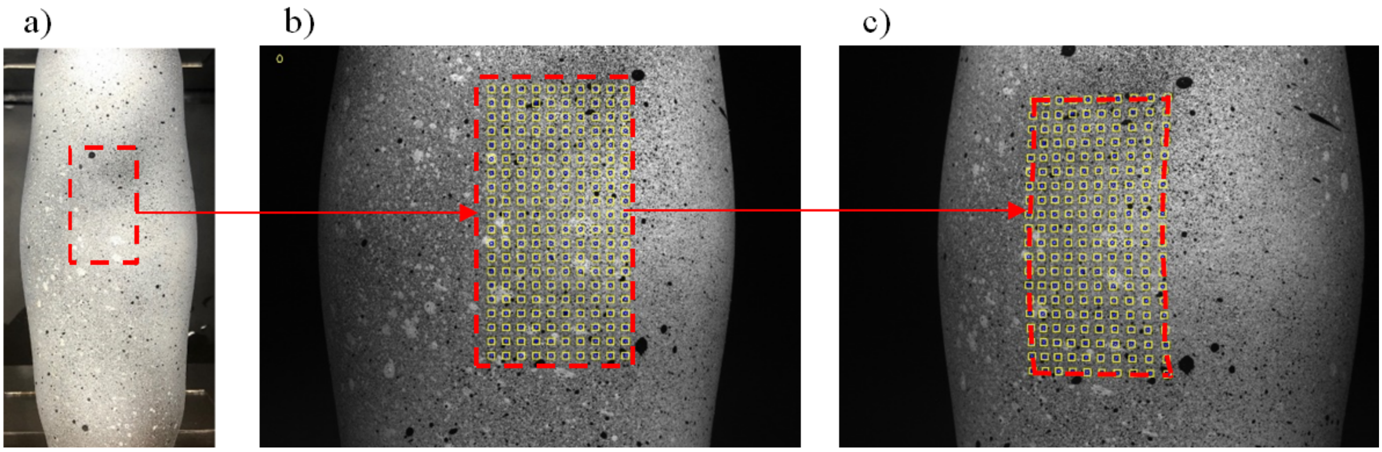


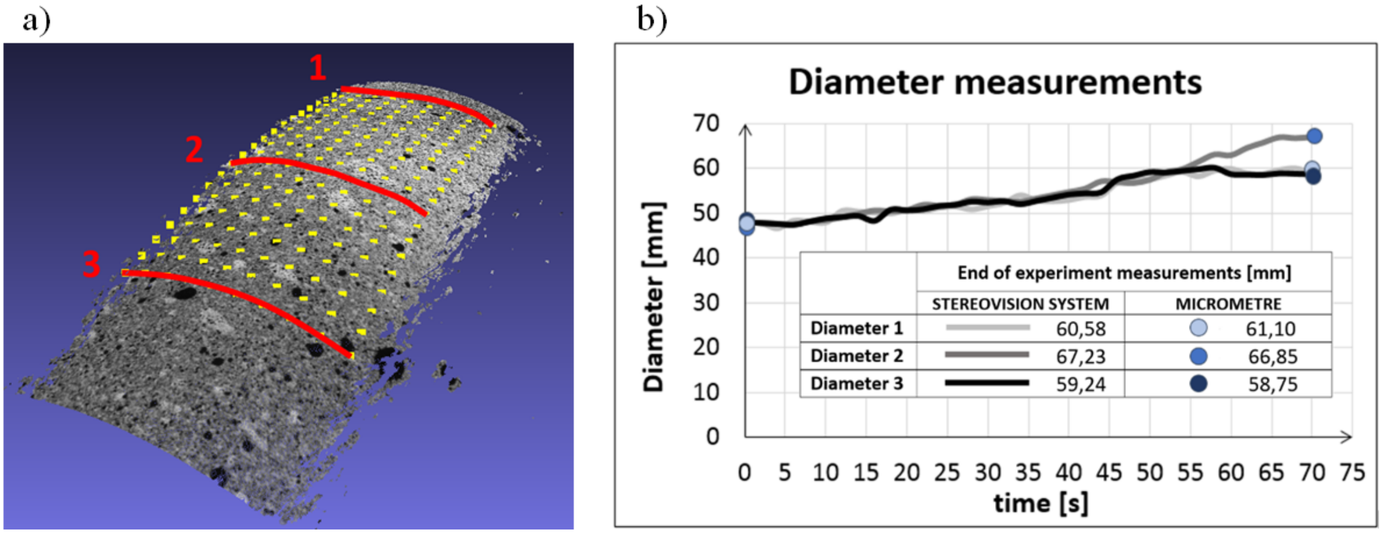
Fig. 4. Stereovision system process of tube profile reconstruction: a) tube during deformation process with analysed area, b) pattern generated by stereovision system – left camera view, b) patterned area reconstructed on the right camera view

The result of the correlation is a matrix in which the element with the highest value indicates the location of the detected object with one pixel resolution. To increase the measurement resolution sub-pixel detection was used, and the resolution of the correlation matrix was increased by means of bi-cubic interpolation. As a result of the above mentioned method a 50-fold increase in resolution was obtained. Hereby, it was possible to determine the position of points on the image with a resolution of 0.02 px, which is about 1 μm part of the sample surface. The coordinates of the sample surface points registered in both images allow to determine their position in 3D. In this way, cloud points with optional object texture can be generated. The resulting reconstruction of the sample surface with a diameter of 48 mm is shown in Fig. 5.

After obtaining information about 3D geometry and determination of measurement tags, Fig. 4b the software is ready to calculate the deformations occurring on the sample surface during the hydroforming process. Based on the tags displacement for each frame of recording movie axial and circumferential deformations and strains can be calculated.

4. Strain measurements on TH stand

In order to check the suitability of the described above stereovision system built for the TH stand free tube hydroforming experiments of steel seamless tubes have been conducted (material: E235 + N, tube dimensions: 48×2). The obtained results were used to check two issues: how and with what accuracy the system interprets the measured tube geometry and whether the obtained history of strain indicates the existence of an uniform deformation stage (see section 2). To answer these questions, some cases of free tube hydroforming experiments were conducted, and the obtained deformations were analysed and measured with the use of the vision system. During the experiments on the TH stand, the data from the stand sensors were recorded and sent to the controller to be downloaded and analysed after tests. At the same time the vision system recorded the geometry of the measuring sections of the tube sample and it was possible to measure the selected diameters situated on the tube surface. In order to verify the stereovision system, a few cases of free hydroforming seamless steel tubes were analysed for the selected tube diameters.



	End of experiment measurements [mm]			
	STEREOVISION SYSTEM		MICROMETRE	
Diameter 1	—	60,58	●	61,10
Diameter 2	—	67,23	●	66,85
Diameter 3	—	59,24	●	58,75

Fig. 5. Diameter measurements for 48×2 steel seamless tube: a) diameter locations 1, 2 ,3, b) diameter history for locations 1, 2, 3 (lines) and diameters measured directly on tube specimen (dots)

The stereovision system reconstructed the section of measuring area and it was possible to visualise the geometry of the surface by means of 3D coordinates and the image of specimen surface. Fig. 7a presents such a reconstruction for seamless steel tube 48×2, where yellow tags correspond to the space coordinates of tube surface. To compare the results obtained from the stereovision system the direct measurements of the sample diameter before and after the experiment were made. The red lines on Fig. 7a refer to the three diameters measured during experiment, see chart in Fig. 7b. Simultaneously, common diameter measurements (by micrometre) were performed before and after the experiment, and presented on the time diagram in Fig. 5b as blue dots. It can be observed that diameters recorded by stereovision system and measured directly are quite comparable. The comparison of obtained values were collected in the table in Fig. 7b. The homogenous increase of diameter in all analysed locations up to 55 second of experiment can be observed. After that time, a faster increase of diameter 2 occurs, which corresponds to the bulge of the tube in that area. Based on the results from the above-mentioned, and other free tube hydroforming tests, it was found that the system calculates the tube geometry quite accurately. Considering other experiments the possible deviations of the compared values are not greater than 6.5%, which indicates its usefulness during measurements of tube deformation at the TH station.

As stated in section 3, the stereovision system built for the TH stand is able to analyse the entire measurement area recorded by the cameras, so it is possible to obtain deformation distributions of the examined area. In addition, each tag of the measurement area can be considered separately and it is possible to generate an isolated course of deformations over entire experiment time.

The capabilities of the vision system described above, can also be used to verify the second issue, i.e. whether during the free tube hydroforming test a uniform deformation stage can be observed and properly measured. To determine this another series of free tube experiments was conducted. As the confirmation example the results of a 38×2 seamless steel tube experiment that was suspected to have noticeable uniform stage, was presented below. The selected area of the tube recorded during stereovision system measurements is shown in Fig. 6a and b. The system processed pictures of the measured area taken by both cameras, and calculated distributions of strains obtained during the experiment. The result of circumferential and axial strains in final stage is presented in Fig. 6c and d. The obtained strain distributions, both circumferential and axial, seem to be quite homogenous, which confirms the thesis about the occurrence of uniform deformation stage. However, in order to verify this regularity during other moments of the experiment, circumferential strain diagrams were generated for selected points A, B and C of the measurement area (see Fig. 7).

The A, B, C locations were selected as the extremely different based on the circumferential strain distribution, Fig. 7a. The obtained deformation plots for selected locations of the analysed measurement area indicate sufficient convergence even though some value variations occur. Therefore it allows to conclude that in the range of the analysed measurement section the tube deformed quite evenly confirming the uniform stage.

5. Summary and conclusions

It was necessary to build a special measurement system enabling the registration and analysis of tube deformation during the tube hydroforming experiments in order to achieve the main goals for which the TH testing machine was built. The vision system adapted to the TH station was designed and constructed allowing the registration and deformation analysis of tubes formed during experiments. The results presented above, verify the correctness of the measurements using a constructed vision system, and confirm the compliance with real geometry of the tested tubes. An additional advantage of presented vision system was the confirmation of the uniform strain phase occurrence during selected cases of free tube hydroforming experiments. In summary, it can be stated that the presented strain measurement system can be very useful for free hydroforming experiments and research work at the TH testing machine.

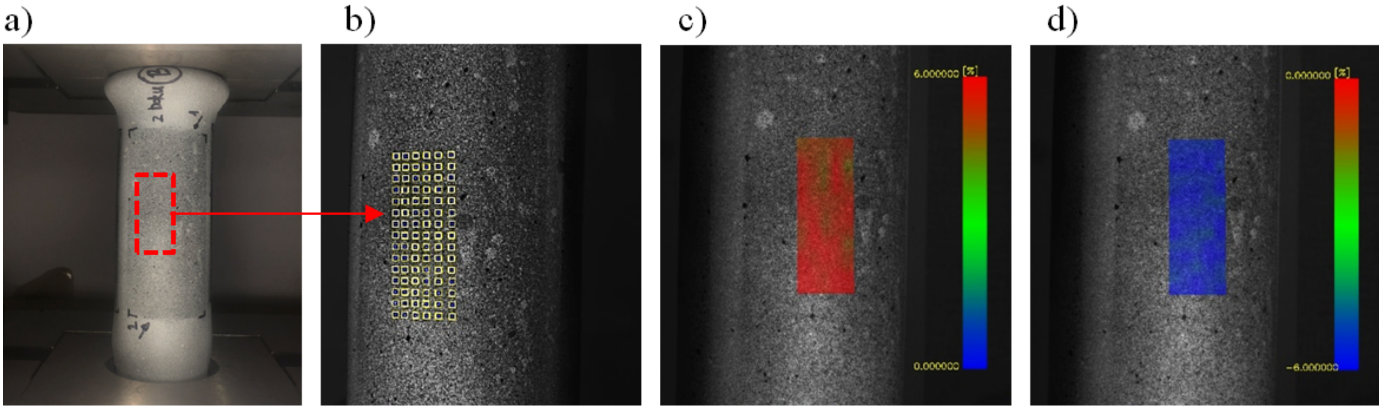


Fig. 6. Stereovision system results for 38×2 steel tube (end of experiment): a) top view of deformed specimen with analysed area, b) left camera view with analysed area (yellow tags), c) right camera view with distribution of circumferential strain of measured area, d) right camera view with distribution of axial strain of measured area

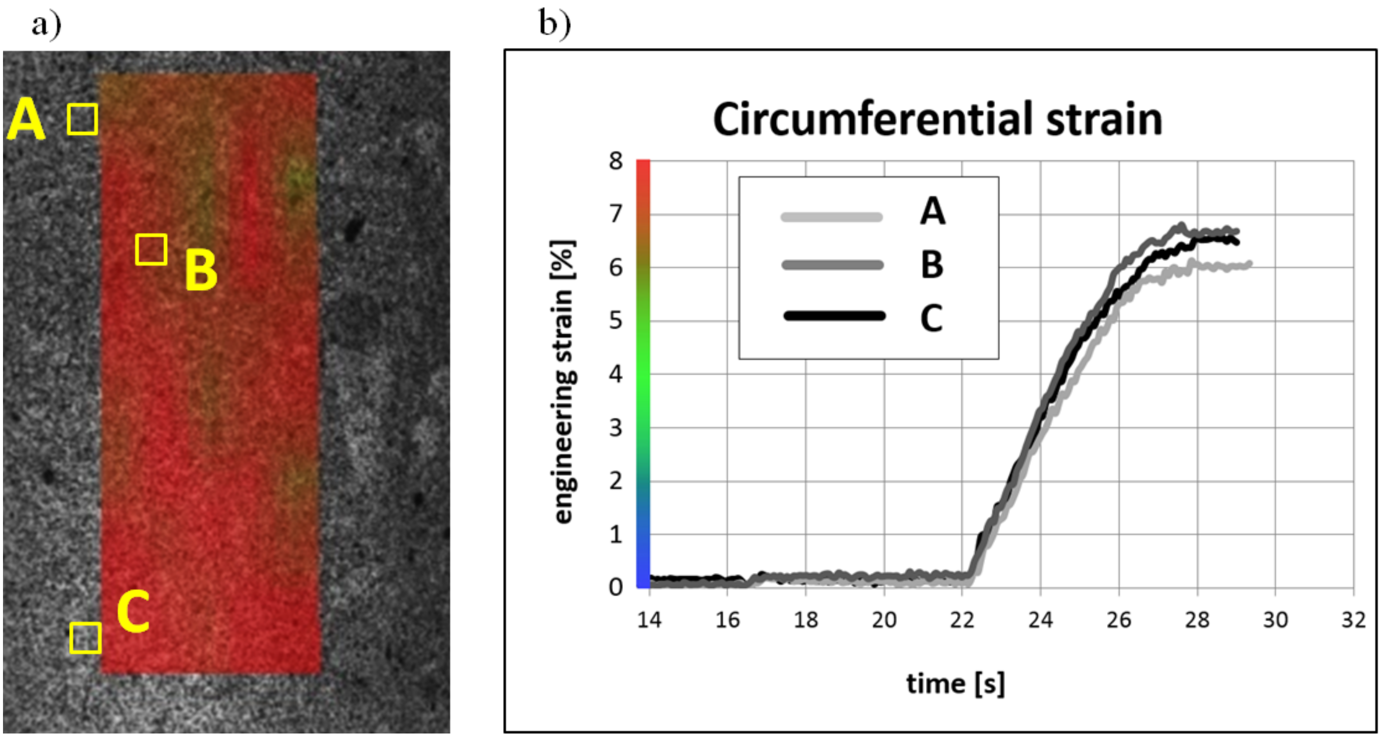


Fig. 7. Circumferential strain results obtained from stereovision system for tube specimen formed on TH machine: a) strain distribution of analysed area with selected points A, B, C, b) circumferential strain history plots of selected points A, B, C

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