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A VISION SYSTEM TO SUPPORT DETERMINATION OF MECHANICAL PROPERTIES OF TUBES REQUIRED FOR COMPUTER MODELLING OF TUBE HYDROFORMING

HANNA SADŁOWSKA*, ANDRZEJ KOCAŃDA, CEZARY JASIŃSKI, ŁUKASZ MORAWINSKI

Warsaw University of Technology, Faculty of Production Engineering, 85 Narbutta St.,
02-524 Warsaw, Poland
**Corresponding author: h.sadlowska@wip.pw.edu.pl*

Abstract

Reliability of computer modelling of tube hydroforming depends strongly on mechanical properties of tubes, which are difficult to determine and sensitive to tube production methods. Some developments in experimental set-up and the vision system for tensile tests of specimens cut from the tube in the axial and circumferential directions are presented. The high accuracy of results obtained by this system has been crucial for determining strains in the tested tubes as well as flow curves for tube material and its planar anisotropy.

Key words: tube, Hydroforming, vision system, mechanical properties of tube, computer modelling, anisotropy of the tube material

1. INTRODUCTION

Tube hydroforming belongs to metal forming processes, which are used to form complex shapes from tubular blanks. The blank is usually placed between the two die halves and next subjected to controlled inner pressure (e.g. exhaust system components). In some cases, additional axial feeding of tube material into the deformation zone is performed (e.g. T and X – shapes). Conventional investigation of tube hydroforming process by means of trial and error has been expensive and time-consuming. The application of computer modelling has improved considerably the process development and became an essential tool for the investigation of the process parameters affecting the final product.

Computer modelling of tube hydroforming depends strongly on mechanical properties of the tubes. Tube production methods have a great influence on these properties. Some tubes are produced from sheet metal by roll-bending, welding and sizing operations. Then mechanical properties of tubes could be estimated by using standard properties of the sheet metal found before bending (Levy et al., 2004). It would be more accurate to use a tensile test of flattened part of the tube as presented by Kulkarni et al. (2004), Hwang et al. (2009) or Olabi and Alaswad (2011). However, this method is not suitable for small diameter tubes with relatively big wall thickness. In such cases flattening of specimen introduces some strains and residual stresses into the tube material. It results in different material properties of these specimens as compared with the properties of initial tube. Sang et al. (2007) indicated that the mechanical properties obtained from the free bulging test of tube were more reliable for numerical analysis. However, the tube bulging test requires specialized and expensive experimental setup and the range of tested tube diameters is usually limited. Tensile test is still an interesting choice to find tube material properties with relatively low cost of experiments.

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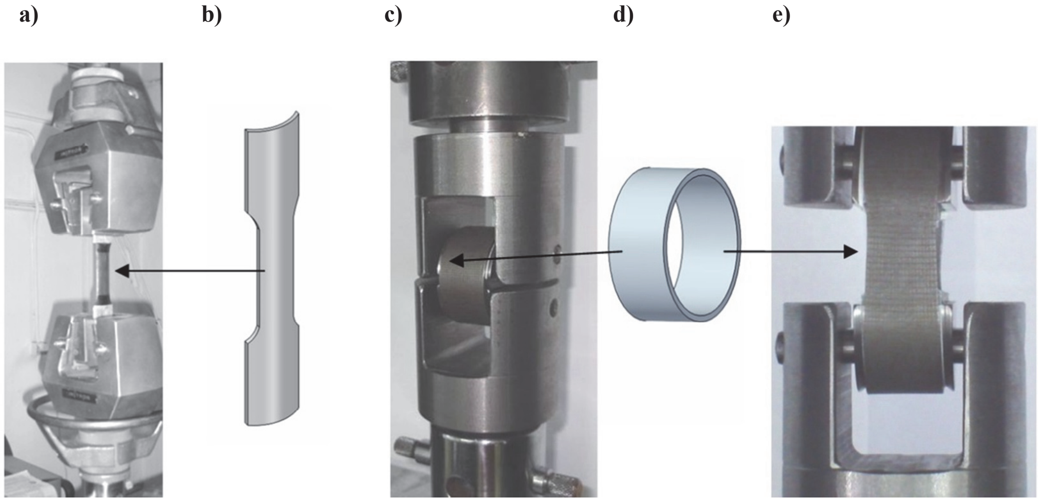

Fig. 1. Specimens cut from the tube in axial (b) and circumferential (d) directions, and gripping systems: a – mechanical grips, c - view of mounted ring, e - view of elongated ring.

It should be pointed out, that seamed tubes have a groove weld and heat-affected zone for which material properties are quite different from the sheet metal properties. It is not a serious problem for most of the products. However, some automotive components cannot be hydroformed with using seamed tubes because of high quality requirements. As s result, seamless tube produced by drawing is the only choice to meet these requirements. In such tubes, the material grains are elongated in the axial direction which results in different mechanical properties of tube material in circumferential and axial directions. This anisotropy would have a considerable influence on the results of numerical simulations. Kim et al. (2006) used the incremental theory of plasticity for an anisotropic material to show an influence of anisotropy parameter on prediction of forming limit for tube hydroforming. Swillo et al. (2009) presented some method to determine the mechanical properties in the circumferential direction by using tensile testing of specimens cut longitudinally from the tube without flattening. Special image processing was used to determine the deformation of these specimens with the curvature in the width direction. Sadlowska and Kocanda (2010) presented some essential considerations and experimental set-up for determining tube material properties in the circumferential direction by means of tensile tests of rings cut from the tube. They found that specimens cut out in the axial direction of the tube indicated higher strain hardening effect than ring specimens cut out in the circumferential direction of the tube. This difference was related to the production method of such tubes, i.e. to cold drawing process in which material grains were elongated in the axial direction. Experimental method was based on analysis of video images.

In this paper some developments in experimental set-up and the vision system for tensile tests of specimens cut from the tube in the axial and circumferential directions are presented. The high accuracy of results obtained by this system has been crucial for determining strains in the tested tubes as well as flow curves for tube material and its planar anisotropy.

2. TENSILE TESTS

Tensile tests of the specimens cut from the tube were carried out by means of the universal testing machine. General geometry of specimens and gripping systems are shown in figure 1.

As for tensile testing of specimens cut from the tube in axial direction (longitudinal specimens), common mechanical grips were used. However, the specimens cut from the tube in the circumferential direction (rings) required special experimental set-up with floating inserts over which the ring was mounted. Friction between the specimen and the inserts was minimized due to application of Teflon tape. The gauge part of each specimen surface was covered by the grid. Geometry of gauge part of these specimens was characterized by substantial curvature, which caused difficulties in the online registration of strains during tensile tests. Hence, inspection of the grid deformation during a tensile test was performed by means of a special experimental set-up with a vision system.

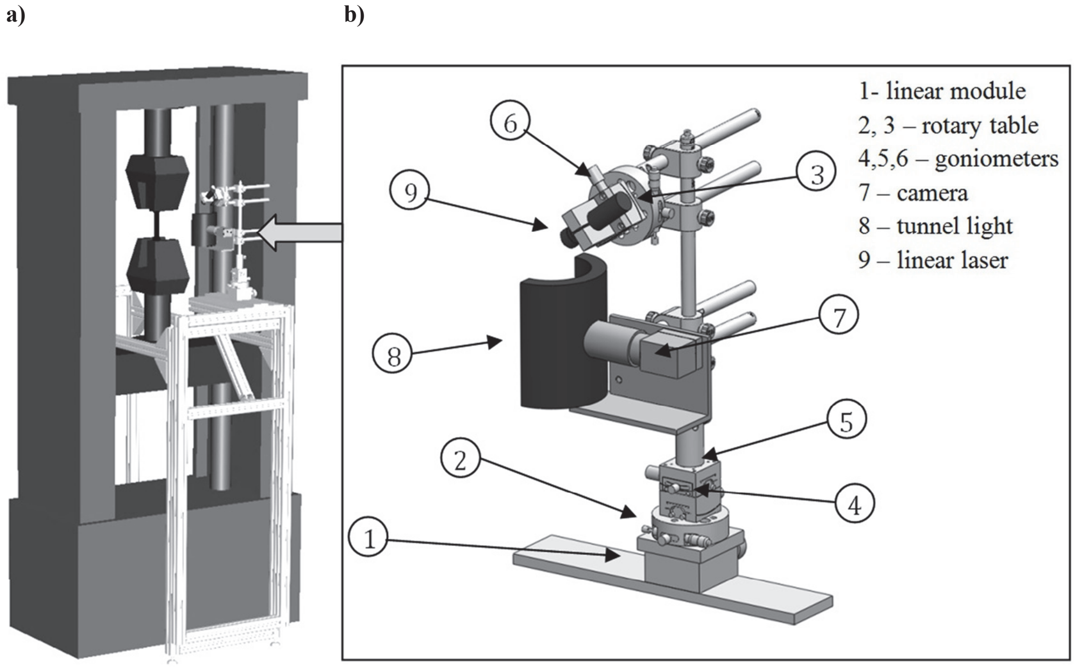

Fig. 2. Universal testing machine (a) with special stand to mount vision system (b).

3. VISION SYSTEM

In order to increase the accuracy of strain determination, special stand with mounting system for video cameras and linear laser was designed, figure 2. The main idea for measurements with a vision system was to get grid nodes on specimen surface and curvature of specimen alternatively on the same deformation stage. Thus, one camera was enough to find the positions of grid nodes in 3D space. It was essential to have uniform illumination of the specimen surface, which was given by a special tunnel light. What's more, the exact positioning of camera and laser during calibration and measurement required preparation of special stand with rotary tables, linear module and goniometers.

Determination of curvature was possible due to the laser line, which crossed the grid lines as shown exemplary in figure 3. Video images of specimens were taken alternately – one image of lightened grid lines (an even number) followed by one image of laser line (an odd number). Switching the lighting and laser on and off was synchronized with camera with digital control unit NI USB 6525, figure 4.

Images of the grid and laser line have been used in the way shown schematically in figure 5. Odd number images of grids have been used to find the edge of the laser line, which has been transformed to outline the specimen shape. Even number images have been compared with standard cross to find grid nodes. Thus, coordinates of grid nodes after each step of deformation could be determined. Next, these grid nodes have been placed on previously determined geometry of the specimen. Finally, the 3D

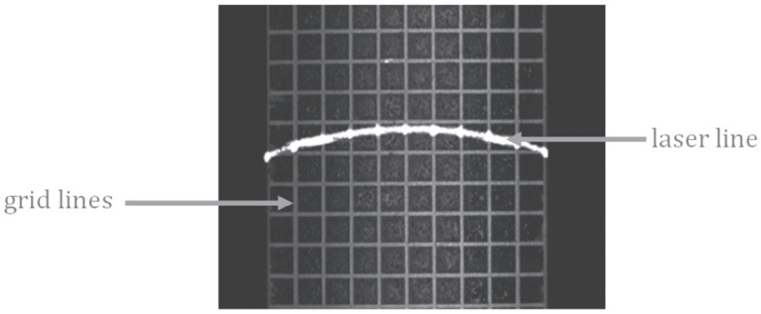

Fig. 3. Example of laser line crossing the grid on the curved surface of longitudinal specimen.

image of the specimen with nodes has been transformed into a 2D image. This procedure decreases the error introduced to 3D image by the lenses of a camera.

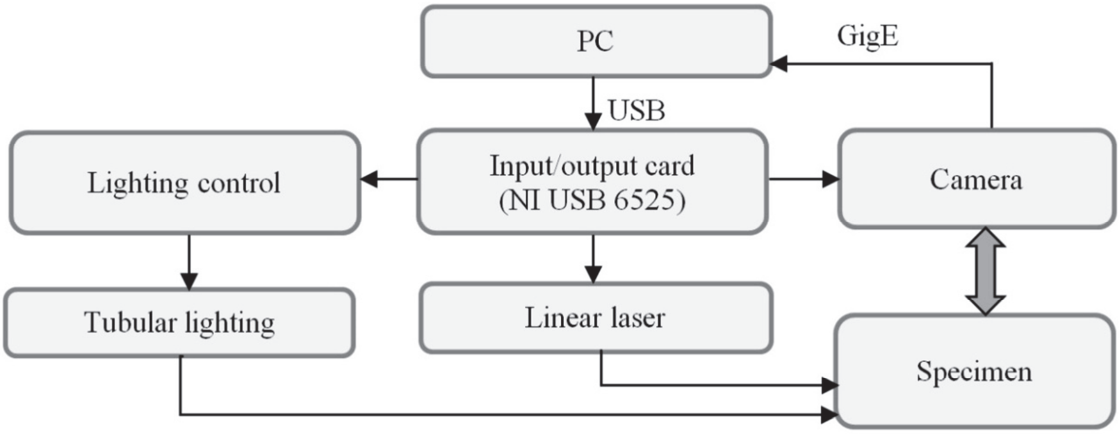

Fig. 4. The control scheme for taking images.

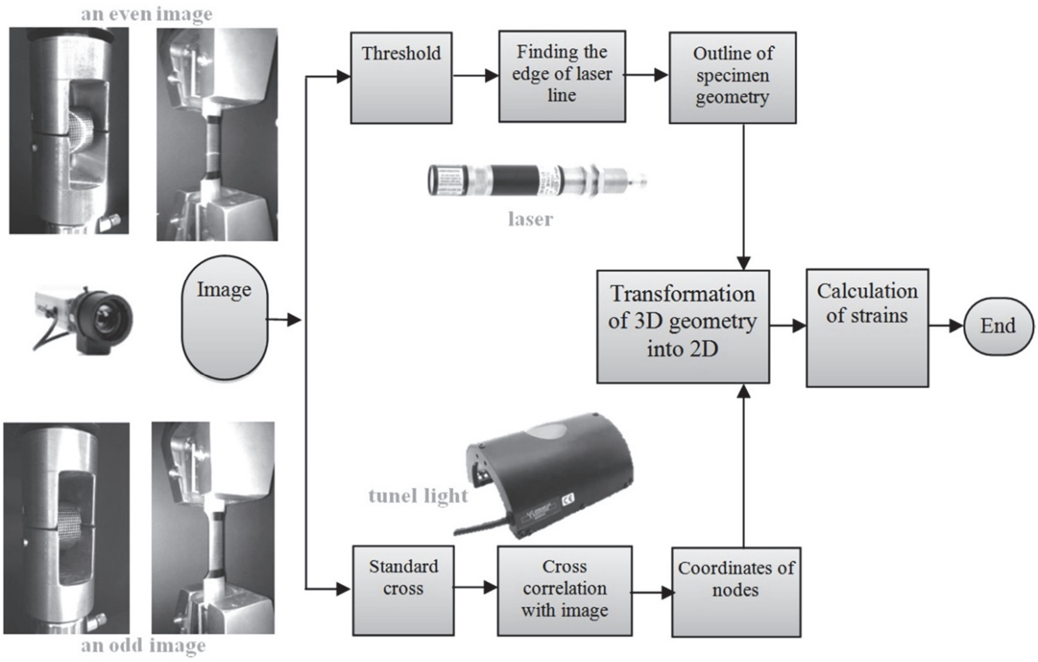

Fig. 5. Schematic presentation of the procedure to determine the strains in deformed specimen.

Having obtained sets of coordinates for the nodes, strains in two main directions on a specimen surface are calculated. Figure 6 shows the capabilities of application created for the needs of vision system - the distribution of strain values for the characteristic deformation of the longitudinal specimen.

The above-described method makes it possible to obtain strain distribution at the time of the specimen surface measurement. Due to this method a detailed analysis of the history of deformation of the selected area could also be performed. These possibilities are shown as an example in figure 6 for tensile test of longitudinal specimen for both axial and transverse directions. It is also possible to combine the strains with corresponding course of the force recorded during a tensile test. The stresses calculated by using force values combined with strains can give the flow curves for tube material for both axial and circumferential directions, figure 7a. Next, axial strains (figure 6a) in combination with the transverse ones (figure 6b) allow obtaining information about the plastic anisotropy of the tube material, figure 7b. The detailed information on determining the stress-strain curves has been described by Sadlowska and Kocanda (2010) and by Sadlowska (2011).

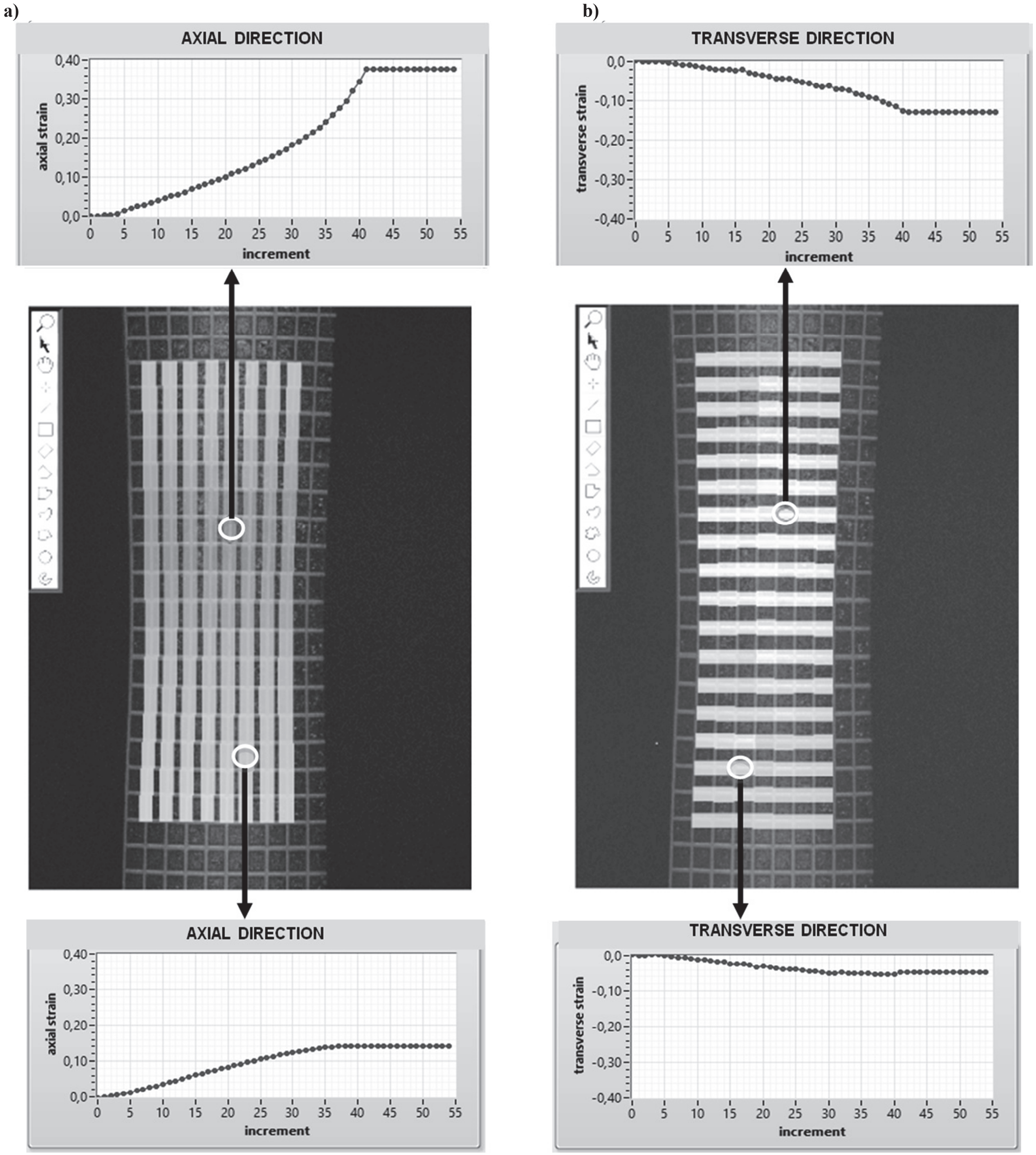

Fig. 6. Axial (a) and transverse (b) strains of longitudinal specimens determined by means of the vision system.

3. COMPUTER MODELLING OF TUBE HYDROFORMING

Knowledge about the plastic deformation behaviour of tube material is a key issue in modelling of hydroforming processes characterized by complex strain and strain states. By taking this behaviour into account, it is possible to build a numerical model, which allows not only examining the influence of process parameters, but also it is helpful in designing the process and tooling. Various models have been examined and the model with 2D elements (four-node, isoparametric, arbitrary quadrilateral) for axisymmetric calculations has been found as best as a conclusion from a comparison of calculated and experimental results.

In this paper the authors focus on identifying the material properties of seamless cold drawn tubes ϕ48x2 mm made of steel E235 + N (EN 10305-1), which are subjected to free bulging by inner pressure. These properties are then used in attempts to analyze the influence of process parameters on the behaviour of the tubes during hydroforming. Considerations are based not only on the results of the experiments but also on the results obtained by computer modelling of the process.

It is crucial for numerical model to contain the most detailed information about the material properties in order to reflect the actual process conditions. In view of the fact that the samples used for hydroforming were cut from seamless cold drawn tube, some differences in the properties of material in relation to the characteristic directions on the tube (i.e. axial and circumferential) would be expected. To confirm this hypothesis, the described earlier experimental set-up with vision system has been used.

Longitudinal and ring samples cut from tubes have been subjected to tensile test on the testing machine. Information concerning the tensile strength and strain measurement was the basis to get the stress-strain curve. Figure 7a shows the curves obtained for the axial direction of the tube (orange curve obtained in a tensile test for longitudinal specimen) and circumferential direction of the tube (blue curve obtained in a tensile test for ring specimens), then figure 7b depicts the distribution of the coefficients of planar anisotropy.

Despite the relatively small differences in the curves obtained for axial and circumferential directions, they proved to be very important for getting acceptable results of numerical simulations of free (dieless) tube hydroforming. The tube has been subjected at the same time to free radial expanding pro-

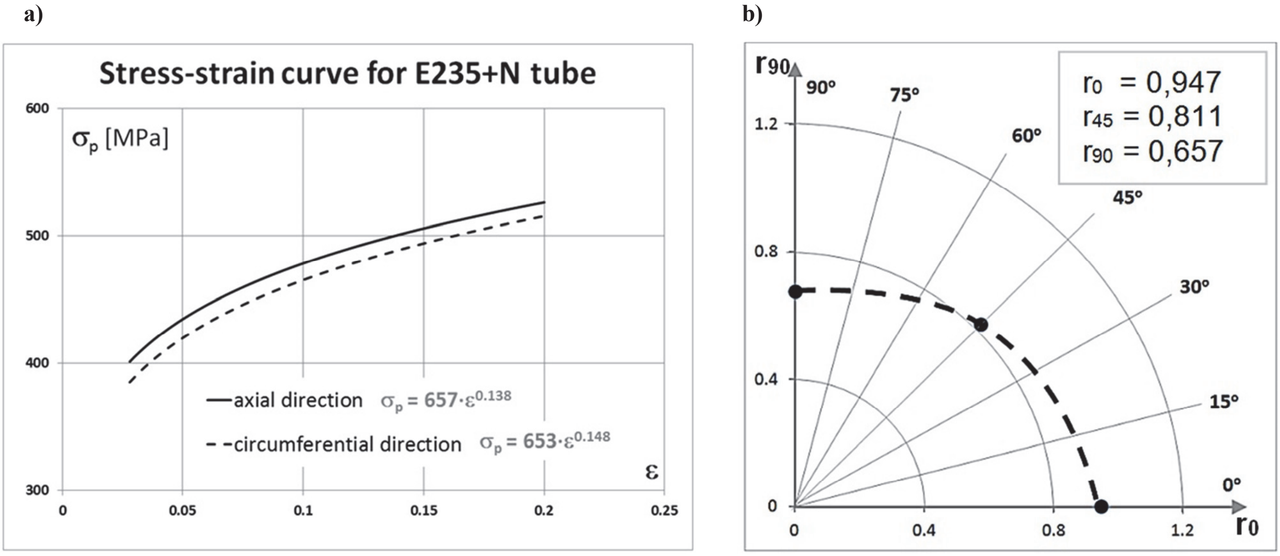

Fig. 7. Material properties of seamless cold drawn tubes made of steel E235 + N: a) -stress-strain curves for axial (orange curve) and circumferential (blue curve) directions, b) – coefficients of planar anisotropy of a tube material.

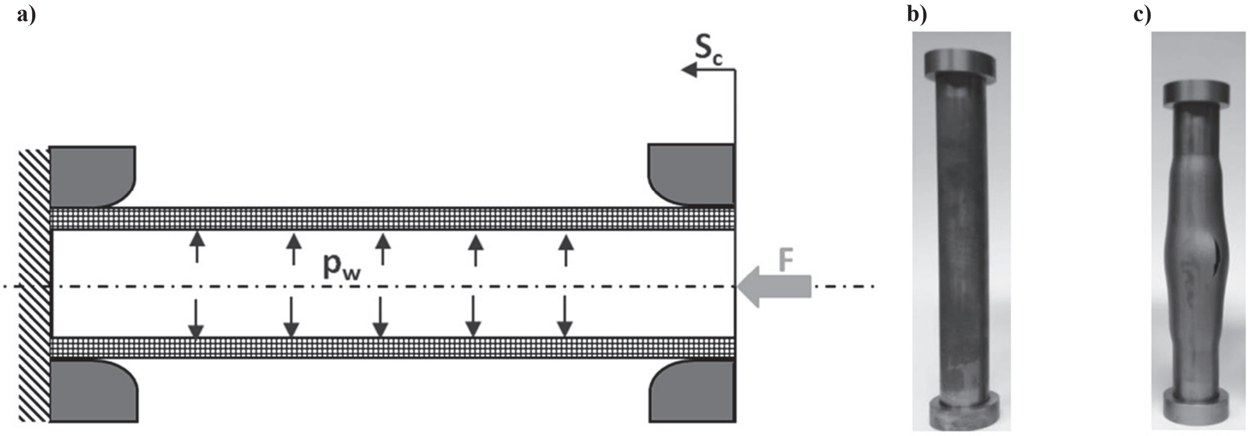

Fig. 8. Free hydroforming of tube: a) schematic presentation of the process and main parameters, b) initial shape of tube specimen with special mounting ends, c) final shape of tube specimen after fracture occurred.

cess by inner pressure p_w and compression by the axial force F to reduce tube length S_c, figure 8. The experiments were carried out on the special testing machine TH in the Department of Metal Forming, Warsaw University of Technology, Sadlowska (2013).

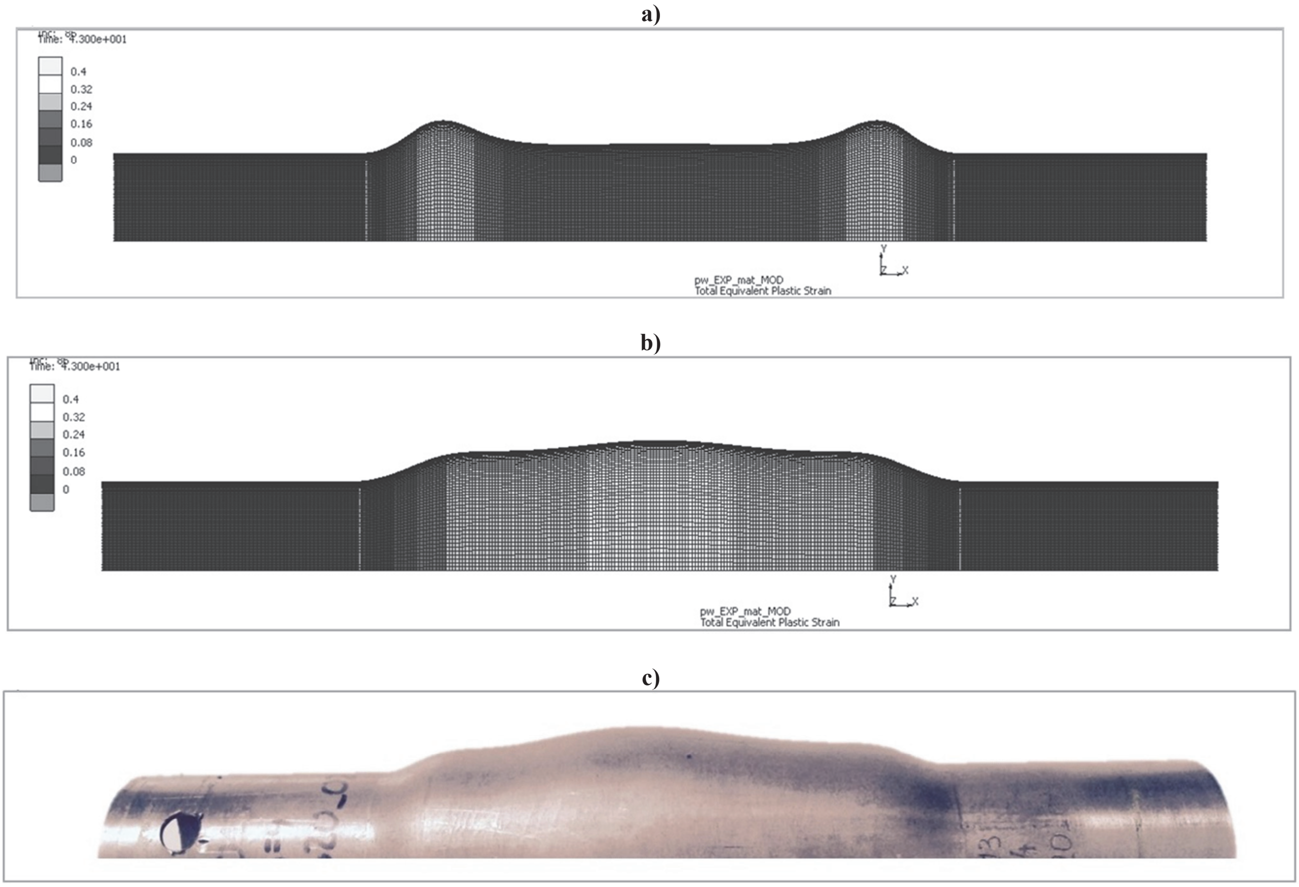

Fig. 9. *The results of computer modelling of tube hydroforming for isotropic material model (a) and anisotropic material model (b) compared with the result of experimental hydroforming (c).*

Computer model (MSC.Marc) of the hydroforming process was prepared exactly for the same geometry and loading conditions as in the experimental tests. There were two sets of material properties taken into account.

The first one assumes the same material properties of each part of the tube and is based on the flow curve determined from the results of tensile tests of longitudinal specimens using a classic Huber-Mises-Hencky model. It could be regarded as an isotropic model of the tube material. The second model takes the different material properties into account with respect to the axial and circumferential directions in the tube. For this purpose, MSC.Marc software uses a built-in Hill's (1948) model. It means that the classic isotropic yield function (used in Huber-Mises-Hencky model) has been modified by ratios dependent on the planar anisotropy coefficients r_0, r_{45}, r_{90}, see values in figure 7b.

Exemplary results of computer modelling are presented in figure 9 and compared with the results of experiments for the same process parameters. The results of computer modelling of tube hydroforming for an isotropic model of tube material (a) do not correspond with the results of experiments (c). Tube is not bulged in the central part and instead clear folds at the gripping portions are visible. On the other hand, the results of computer modelling of tube hydroforming for material properties, which include description of anisotropy, found by the method described in this paper for two kinds of specimens, show very good agreement of calculated and experimental shapes of hydroformed tubes (b). The good coincidence computer modelling results based on an anisotropic model with experimental results proved by axial strain comparison, figure 10.

Thus, the differences in the properties obtained in the axial and circumferential directions of the tube, which seem to be relatively small (see figure 7a), are really very significant in terms of their effect on the shape of hydroformed tube. This would be particularly important when designing industrial hydroforming processes because the cost of trial and error method would be considerably limited.

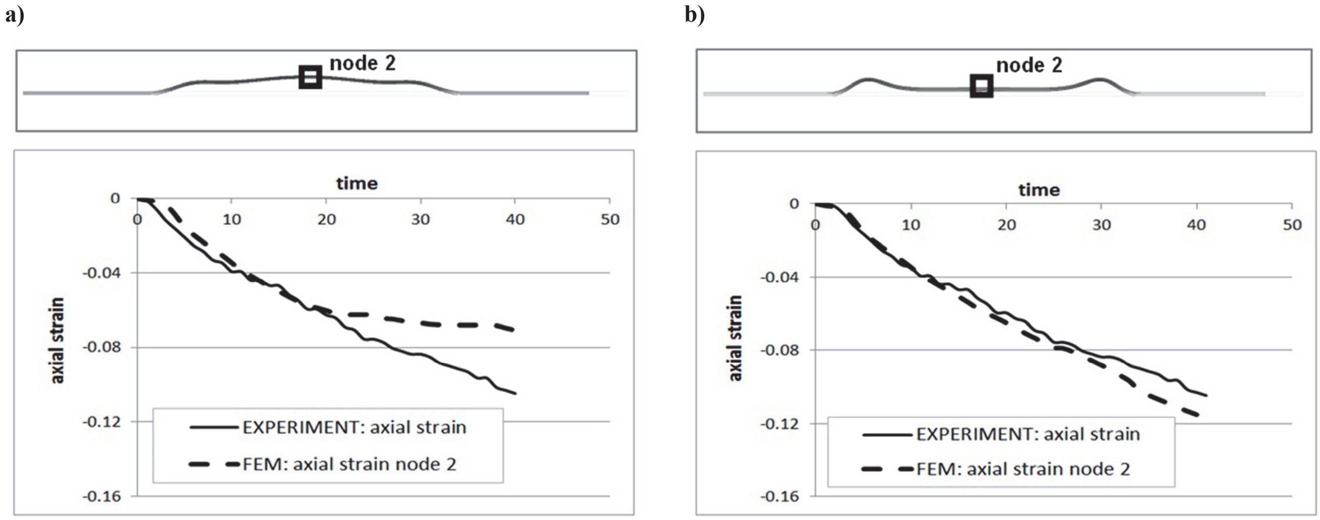

Fig. 10. *Axial strains obtained by FEM simulations (green line) compared with experimental results (orange line) for: a) Hill's (anisotropic) material model, b) Huber-Mises-Hencky (isotropic) material model.*

4. CONCLUSIONS

1. Experimental set-up for tensile tests of specimens cut from the tube in the axial and circumferential directions supported by the vision system has been successfully applied. The high accuracy of results obtained by this system has proved to be crucial for determining strains in tested specimens characterized by convex surfaces.
2. Tensile test results for longitudinal and ring specimens cut from a tube have been used to provide data on the tube material anisotropy.
3. Introducing description of the tube material anisotropy into computer modeling of tube hydroforming process has been crucial to get very good agreement of calculated and experimental deformation of hydroformed tubes.

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SYSTEM WIZYJNY WSPIERAJĄCY WYZNACZENIE WŁASNOŚCI MECHANICZNYCH RUR NIEZBĘDNYCH W KOMPUTEROWYM MODELOWANIU KSZTAŁTOWANIA HYDROMECHANICZNEGO RUR

Streszczenie

Poprawność komputerowego modelowaniu kształtowania hydromechanicznego rur zależy w dużym stopniu od własności mechanicznych rur wprowadzonych do obliczeń. Własności te zależą od metod produkcji rur, są trudne do wyznaczenia i różnią się od własności standardowo wyznaczanych dla danego materiału na podstawie badań próbek z blach czy prętów. Przedstawiono więc specjalną metodę wykorzystującą system wizyjny dla wyznaczenia odkształceń próbek wiosełkowych i pierścieni wyciętych z rur odpowiednio w kierunku wzdłużnym i porzecznym. Uzyskana wysoka dokładność wyznaczania odkształceń w rozciąganych próbkach wyciętych z rur jest podstawą do dokładnego określenia krzywej umocnienia materiału rury i uwzględnienia współczynników anizotropii.

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