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AN EXPERIMENTAL STUDY OF MATERIAL FLOW AND SURFACE QUALITY USING IMAGE PROCESSING IN THE HYDRAULIC BULGE TEST

SŁAWOMIR ŚWIŁŁO

Faculty of Production Engineering, Warsaw University of Technology, Warsaw/Poland
**Corresponding author: s.swillo@wip.pw.edu.pl*

Abstract

The paper presents a method for the surface shape and strain measurement applied in the determination of metal flow and product quality. Accurate determination of these characteristics in the sheet metal forming operation is extremely important, especially in automotive applications. However, the sheet metal forming is a very complex manufacturing process, and its success depends on many factors. This involves a number of tests that should be carried out to find optimal, yet cost-effective solutions. In this study the author discusses the investigations that are focused on better understanding of the strain values and their distribution in a product, and checking if they do not exceed certain limit resulting in the loss of stability. The hydraulic bulge test was identified as a method most applicable in these investigations, where both theoretical and experimental analysis was conducted.

First, the presented solution in the field of reconstruction of three-dimensional (3D) objects significantly expands the capabilities of the analysis, compared with the solutions existing so far. Second, a new method for the 3-dimensional geometry and strain measurement based on laser scanning technique is presented. Next, the image acquisition process and digital image correlation (DIC) are presented to recognize and analyze the objects taken from camera. The 3D shape and strain analysis presented in this paper offers a valuable tool in the metal products quality control, along with a complete testing equipment for maximum strain calculation just before cracking. The computer measurement system is directly connected to the hydraulic bulge test apparatus, thus providing fast and accurate results for material testing and process analysis.

Key words: strain analysis, sheet metal forming, hydraulic bulge test

1. INTRODUCTION

Methods for the measurement of surface shape or deformation (displacement) generate solutions that are currently and generally applied in various scientific fields. Especially, three methods are widely used by different authors. The first of them is the projection method described in detail by Swillo and Jaroszewicz (2001). The second method is based on the analysis of surface patterns (Swillo, 2001; Koga & Murakawa, 1996; Sirkis, 1990). The third method is laser scanning. In this group numerous solutions are available, and their classification depends on the technique by which the displacements are measured. However, all the contemporary methods – 3D reconstruction of objects or measurements of deformations - are based on a system of image recording by means of a CCD camera. These techniques seem to be very useful in the field of metal forming because they are very effective when strain values have to be determined by the analysis of surface patterns. The method commonly used in studies of the kinematics of the sheet metal forming process is

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stretching of the sheet metal surface with a metal punch (figure 1a). In the present study, to test the plastic forming process, a method of bulging with fluid under pressure the sheet metal disc clamped at the edges has been applied (figure 1b). In this operation, a uniform biaxial stretching occurs, due to which the processed element assumes the shape of a spherical cap. The proposed method of the strain measurement in a bulging process is based on the numerical image processing and three-dimensional object reconstruction. In the last several years, various technical improvements in the method of sheet metal pattern recognition took place, enabling analysis of the local state of strain in industrial sheet metal forming. At the same time, during laboratory tests, many authors have been evaluating the sheet metal quality based on the forming limit curves (FLC), originally proposed by Marciniak (1961), and Marciniak & Kuczyński (1967).

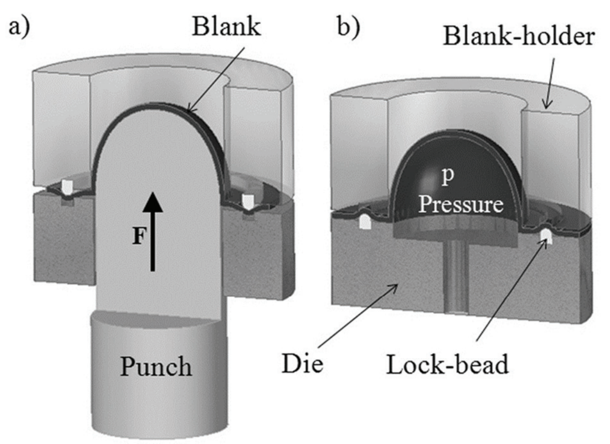

Fig. 1. *Schematics (section view) of the sheet metal forming: a) using metal punch, b) using hydro-bulging.*

Currently, we can find, among others, methods that serve the determination of forming limit curves which, combined with calculations of the deformation occurring in the examined products, provide comprehensive information about the state of the material (for example: Swillo et al., 2000). This solution is based on the use of a metal punch operating on samples with different geometry (figure 1a). These methods are based on either correlation or analysis of the geometry of regular coordination grids. As complementary to the created solutions of automated strain measurement, studies are carried out to detect the crack onset. The, used for many years, method of grids coupled with the image processing has gained numerous solutions. All these solutions are based on the identification of grids applied to the surface of sheet metal. The grids can have a regular or stochastic shape. One of such solutions is a system that enables automatic measurement of lines perpendicular to each other and lying at a distance of 1-5 mm from each other, depending on the nature of the measurement. Studies on the design of systems for automatic strain analysis are carried out by Vialux Company (Feldmann & Schatz, 2006; Feldmann, 2007). The Company has developed a system called AutoGrid used for the analysis of deformation during bulge test. The possibility of plotting the forming limit curves also enables predicting what are the chances for further plastic forming of the sheet metal. Owing to this characteristic of the deformation limit of any sheet material, the collected information allows us to determine if the strain values in areas of the largest product deformation are approaching the limit values.

Another option is a system for the analysis of deformation based on the bulging test using a steel punch (Liewald & Schleich, 2010). The process is performed on a specially designed testing machine, where appropriate optical system with two cameras can record the run of the forming process. Image analysis of the deformed sample area is done by a commercial ARAMIS system made by GOM (Hijazi et al., 2004). The stand with this device is capable of performing a fully automated control of the bulging process using a metal punch The solution uses a digital image correlation technique based on stochastic grids, which, in the authors opinion, are much more efficient as regards the accuracy of the obtained results than the regular grids.

It is believed that, by careful designing of process operations, most of the final product defects and limitations can be eliminated, minimized, or at least controlled. According to the current experimental investigation, all available information to predict the quality of the final products is not sufficient. Therefore the goal is to develop a major parameter that can be used in an assessment of the quality of automotive parts after sheet metal forming.

2. EXPERIMENTAL APPARATUS

Solutions presented in this paper are referring to the three dimensional cases. On the example of bulging test, a new possibility in the field of image processing techniques is demonstrated. These techniques seem to be very useful for the metal forming analysis because they are very effective when strain values have to be determined by the analysis of stochastic surface pattern. A specially designed experimental apparatus for bulging process analysis was assembled (figure 2a). The developed solution comprises a computerized, fully automatic, motorized test stand equipped with optical and vision systems to acquire the data. In the described study, tests of the plastic forming were performed using a method of bulging the sheet metal discs (fixed at the edges) with fluid under pressure. In this operation, a biaxial uniform stretching occurs, producing specimens where the dome is spherical in shape. In this example of the sheet metal forming process, numerous solutions are possible as regards the description of the process kinematics and study of the test conditions under which the loss of stability occurs due to the absence of friction on the tool - die contact surface (Marciniak, 1961). The use of the stand allows running two types of the measurements: basic and complex. The first group of measurements includes recording the run of the plastic forming process in terms of pressure and displacement, while second group includes measurements of the process kinematics and of the shape of the bulged samples. Full description of the bulging process should enable further materials research and development of process control mechanisms. The elements of such control can include, among others, an option for the automatic monitoring of the process run and the possibility of its interruption at a strictly determined stage of deformation.

proposed in the measurement model, each laser-generated section is identified by one camera only, while the assumed axisymmetrical shape of the examined object allows its 3D reconstruction. To obtain rapid (in real-time), continuous (pixel-based), high accuracy (sub-pixel) verification of the geometry of the distorted elements, it was necessary to use measurements based on vision control. The, proposed for studies of the kinematics of the shaped objects, method of outline reconstruction using laser light bases on a temporary outline searched for the examined element subjected to deformation. In addition to the measured contour, a front view of the object (with stochastic grid) is recorded, which enables the reconstruction of a 3D image of the measured sample and determination of the size of deformation.

3. ANALYTICAL MODELING OF THE BULGING PROCESS

The aim of the investigations of the sheet metal forming process is to deepen our knowledge about the factors (phenomena) that restrict this process, during which the material undergoes plastic deformation by drawing, extrusion or redrawing. In this process, the formed object is obtained by mapping its shape on a sheet of metal using a punch and a die (figure 1b). The deformation in the forming process

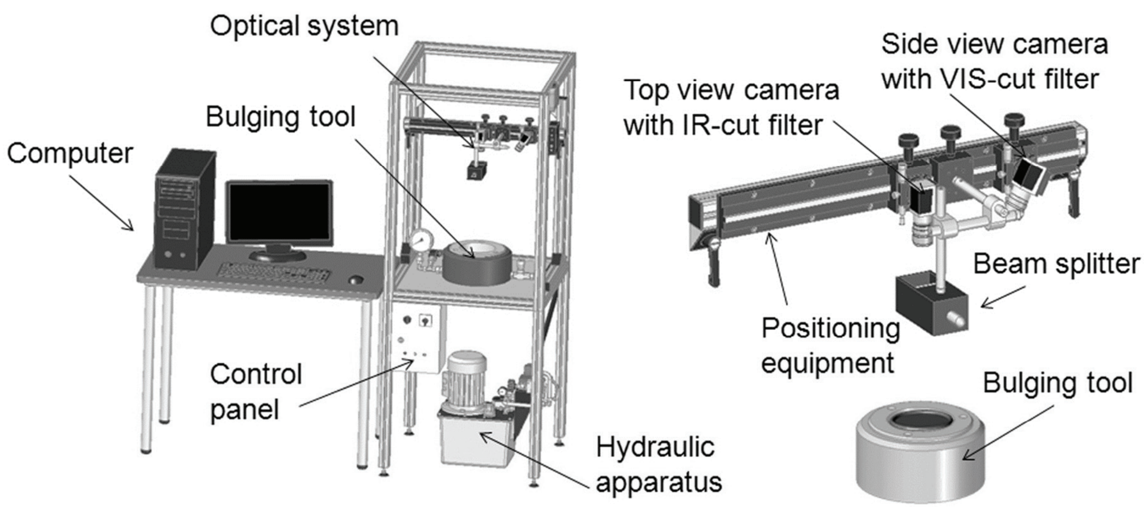

Fig. 2. Schematics of the experimental apparatus for hydro-bulging process: a) the testing stand, b) an optical system to control the bulging process.

The central measurement system in the test stand is an optical system, whose task is to allow a 3D reconstruction of the sheet metal formed (figure 2b). The proposed mathematical model to solve this problem has been based on the author's own research (Swillo et al., 2012). Owing to some simplifications

cannot reach any arbitrarily large values, because some limiting phenomena will occur at a certain stage of the process, disturbing or disrupting even its further course. The main problems include strain localization, cracking, or curling of the sheet metal. The state of biaxial stretching occurring in many forming operations makes the bulge test very useful in this analysis (mainly due to the mere nature of the state of stress). The run of this process is usually considered in terms of the strain occurring in a perfectly flexible thin membrane. According to a mathematical formula relevant to this case, the product of the yield stress multiplied by the actual thickness of the membrane *(σ_p*g)* is constant (Marciniak, 1961). The deformation φ occurring in the center of the dome follows the relationship given below:

$$\varphi = 2ln\left[1 + \left(\frac{h}{a}\right)\right]^2 \quad (1)$$

where: h is the actual dome high and a is the blank radius. In the pure biaxial case where the bulge is a perfect bowl (figure 1), the extreme values of the internal pressure p is given by:

$$p = \frac{2g\sigma_p}{R} \quad (2)$$

where: R is the actual dome radius and g is the thickness at the top of the dome.

Since we have the biaxial uniform stretching, the relationship (2) can be solved by differentiation and simplified to the final form of:

$$\frac{d\sigma_p}{d\varphi}\frac{1}{\sigma_p} = \frac{5}{4} - \frac{1}{4\left(e^{\frac{\varphi}{2}}-1\right)} \quad (3)$$

This relationship allows us to determine in a graphical manner the strain value φ at which the pressure p will reach its maximum for the known hardening curve. Figure 3 shows the results of calculations, where the experimental results obtained on a stand for the test forming using oil were compared with computations made for the membrane theory. The high consistency of the obtained results confirms that the theoretical solutions used to determine the polar limit strain values are correct theoretical assumptions for this area of the metal forming technology.

4. STRAIN MEASUREMENTS ON STOCHASTIC GRIDS

As a result of the performed calculations, the coordinates for the projection of nodal points in a two-dimensional space were obtained. Using information from the second camera, the profile of the bulged sample was determined (according to previous de-

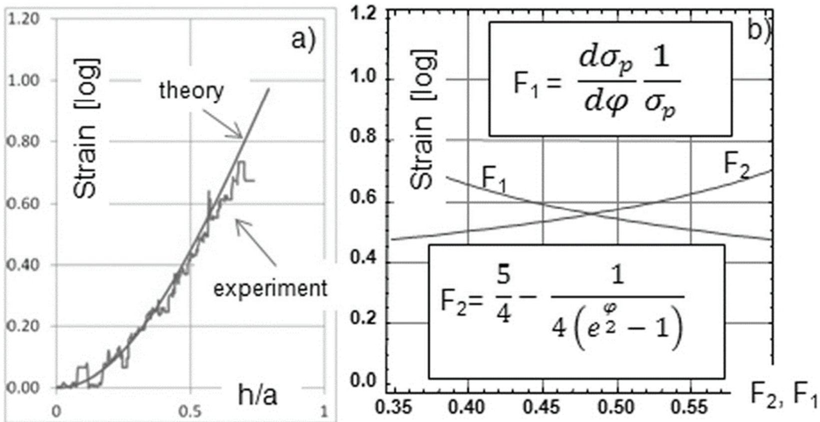

Fig. 3. A comparison of experimental and analytical results of the bulging test: a) strain distribution, b) stress-strain hardening curve.

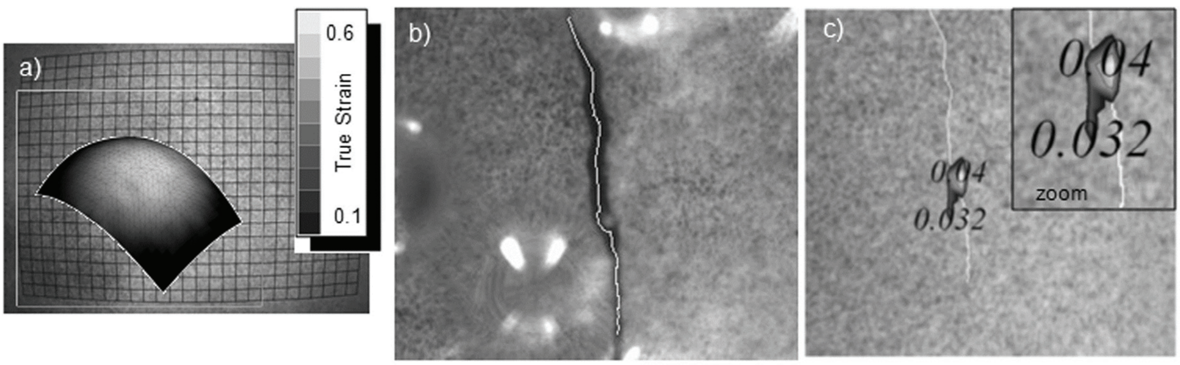

Fig. 4. Displacement and strain calculation: a) global strain calculation using DIC, b) vision inspection (crack localization), c) comparison for the local strain calculation (micro-strain results) and vision inspection.

scription) and, in accordance with the proposed 3D reconstruction algorithm, the third coordinate was specified. Strain measurements were carried out according to the described method of calculations for the main deformation direction and directional displacement gradient measurements (figure 4a).

As an operation complementary to the strain calculation, micro-deformations in the zone of the crack onset during bulging process were determined. The accurate measurement of the forming limit is one of the major issues in plotting of the forming limit curves. The method of image correlation used for this purpose is a highly efficient tool for an accurate measurement of these parameters. The method consists in adding up two values of the deformation. The first value of the deformation is calculated as a result of the identification of the position (image), for which the strain localization occurs (figure 4a). The second value results from the determination of strain that occurs in the crack onset zone (figure 4b). Figure 4c shown the comparison of the calculated strain localization and vision inspection.

5. SUMMARY

The method proposed by the author consists in the identification of an outline of the examined axisymmetrical object, extended to the identification of three-dimensional objects with the possibility of deformation measurements. The use of this approach in the study of the kinematics of the forming process is a solution that has required the development of a mathematical model, the introduction of a number of assumptions to the design of a test stand using this method, as well as the development of methods to process images recorded during plastic forming. The method commonly used in the study of the kinematics of the sheet metal forming is stretching of the sheet metal surface with a metal punch. In this study, the test method used for plastic forming has been bulging with a fluid under pressure of the sheet metal discs, fixed on the edges. In this operation, a biaxial, uniform stretching occurs, resulting in the formation of objects in the shape of a spherical cap. The described example of the process of the sheet metal forming allows obtaining a number of solutions as regards the description of the process kinematics and study of the test conditions under which the loss of stability occurs due to the absence of friction on the tool - die contact surface.

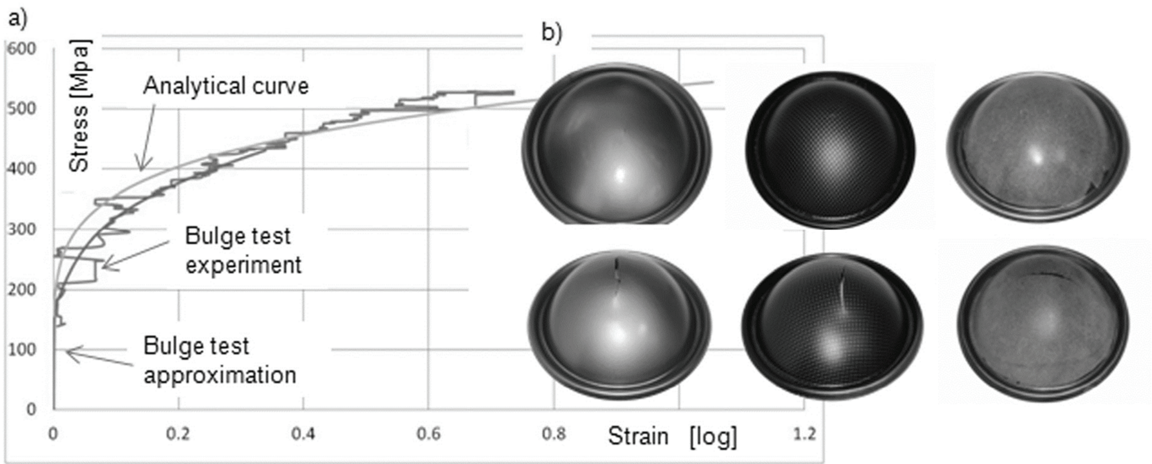

Fig. 5. *a) comparison of experimental results with the hardening curve: b) bulge-samples.*

Finally, based on experimental calculations, the hardening curve for DC04 was plotted, comparing the results with the measurements by the method of uniaxial stretching and with information about the equation of a curve given in the literature (figure 5a). The large scatter in the experimental measurements is due to the lack of a more refined technique for taking precise strain measurements by the method of correlation. Large number of images generated during measurements is an obstacle in precise determination of the deformation history, which is a key factor in the calculation of plastic properties.

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ANALIZA DOŚWIADCZALNA PŁYNIĘCIA MATERIAŁU I KONTROLA JAKOŚCI POWIERZCHNI W PROCESIE WYBRZUSZANIA Z WYKORZYSTANIEM OBRÓBKI OBRAZU

Streszczenie

W artykule przedstawiono metodę pomiaru geometrii i odkształceń w odniesieniu do pól przemieszczeń i końcowej jakości produktu. Dokładna charakterystyka tych wielkości w procesach kształtowania blach jest niezwykle ważna, szczególnie w przemyśle samochodowym. Jakkolwiek jednak jest to proces niezwykle trudny i uzależniony od wielu czynników. Dlatego wykorzystywanych jest wiele testów, w celu określenia charakterystyki materiału. W przedstawionym opracowaniu autor koncentruje się na lepszym zrozumieniu rozkładu odkształcenia i jego koncentracji prowadzącej do utraty stateczności. Zaproponowana został metoda hydro-wybrzuszania, gdzie przedstawiono dwa rozwiązania doświadczalne i analityczne. W pierwszej części przedstawiono rozwiązania w zakresie rekonstrukcji trójwymiarowej, które znacząco rozszerzają możliwości w stosunku do tradycyjnych metod optycznych analizy kształtu. Następnie zaprezentowano wyniki analizy obrazu z wykorzystaniem korelacji, wskazując na znaczne ułatwienia w rozwiązywaniu problemów wyznaczania odkształceń i pomiaru kształtu dla przedstawionego przykładu, jak również dla identyfikacji miejsc potencjalnych pęknięć. Dzięki sprzężeniu urządzenia testującego z układem komputerowym możliwe jest szybkie i precyzyjne przedstawienie końcowych wyników pomiarów własności materiału.

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