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A NEW APPROACH TO EXPERIMENTAL TESTING OF SHEET METAL FORMABILITY FOR AUTOMOTIVE INDUSTRY

Advanced vision method of analysis of the Erichsen cupping test based on laser speckle is presented in this work. This method proved to be useful for expanding the range of information on material formability for two commonly used grades of steel sheets: DC04 and DC01. The authors present a complex methodology and experimental procedure that allows not only to determine the standard Erichsen index but also to follow the material deformation stages immediately preceding the occurrence of the crack. Accurate determination of these characteristics in the sheet metal forming would be an important application, especially for automotive industry. However, the sheet metal forming is a very complex manufacturing process and its success depends on many factors. Therefore, attention is focused in this study on better understanding of the Erichsen index in combination with the material deformation history.

Keywords: vision system, defect detection, Erichsen cupping test, laser speckle

1. Introduction

High quality expectations in the automotive industry lead to constant improvement of technologies for more and more complex manufacturing processes of elements made by means of sheet metal forming. Computer modeling is a widely used tool in the industry. It covers a wide range of information on geometry and process kinematics, allowing for the optimal development of tooling design, predicting tool life, selection of presses and assessment of the material's ability to obtain required deformations [1,2].

In the process of continuous search for solutions that ensure high quality of the product, the grade of material to be deformed has also been crucial. Therefore, intensive work is being carried out to develop a more reliable and quick method of assessing the possibility of avoiding the formation of product defects [3,4]. The currently applied solution in this field in industry is the experimental testing of the delivered material properties in the factory laboratories. The typical properties of the material, such as hardness, yield strength, tensile strength or elongation, are determined. However, they are not sufficient to specify forming limit conditions [5]. The basic evaluation of so called sheet metal formability has been performed by means of strain hardening, anisotropy or forming limit strain [6]. Such an assessment significantly affects the ability to predict the behavior of the sheet metal during forming and obtaining a specific geometry of the product and its mechanical properties. Therefore, in the process of developing sheet metal forming, standard experimental methods have become very helpfull, such as the Erichsen test [7]. The energy solution commonly used in this respect (finding a decrease of the force during sheet metal deformation indicating crack appearance) has often been replaced by more advanced assessment methods. Thus, Erichsen tests are carried out with the use of techniques supporting a more accurate sheet metal cracking evaluation, which include, for example, vision techniques (ARAMIS system) [8]. These techniques are supported by numerical image processing solutions and advanced user interfaces as well as fast data transfer protocols to the computer, leading to automation of the entire measurement process and increasing the accuracy of measurements.

However, despite very advanced computer simulations and precise experimental tests, sheet metal forming processes planned for implementation in industrial conditions continue to result in some surface defects [9]. The reasons are to be found in two groups of factors: technological and material. In the first group of factors, we can distinguish variable contact conditions on the tool surface, which in some way could be compensated during computer simulation. The second group of factors includes the variable strength parameters of the sheet metal, resulting from its insufficient quality. Even small differences in the quality of subsequent batches of sheet metal (meeting traditional delivery standards) may ultimately lead to distortions in forecasting potential surface defects, which include strain localization or sheet metal cracking.

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Currently, attempts to solve the problem with surface defects in industrial sheet metal forming processes are mainly focused on effective computer modeling of the technological process [10] and the development of an effective technique for quality control of products after the process. The most commonly used solutions are: vision techniques [11,12], eddy current testing methods (ET) [13], or laser sensors (laser displacement sensors) [14].

However, due to increasing accuracy in computer simulations (FEM) [15] and in typical measurements of forming limit (e.g. FLD – Forming Limit Diagram) [16] for commonly used deep-drawn sheets, the quality of the delivered material is the most uncertain and least recognized area for obtaining input data for computer simulation. Therefore, the authors draw attention to the necessity to change the current point of view on description of limiting forming strain and place more attention to new areas of experimental analysis of sheet metal forming. First of all, development of visual methods should enable experimental assessment of sheet metal formability based on the history of deformations, and not only the detection of the final defect. This will allow to show existing differences in the properties of the same sheet metal grade but from different suppliers. Second, the development of a new experimental way to assess the final quality of the product, based on the analysis of changes in the surface geometry, and not on the assessment of its final state would be very helpful. This in turn will allow for an efficient (online) indication of defective products during the manufacturing stages.

2. Experimental method

The technical stage of finding new experimental tests for the assessment of mechanical properties of sheet metals was initiated at the beginning of the 20th century [17]. These tests were aimed at comparing the tested materials in terms of their formability. Popular experimental methods allowing to obtain two different deformation mechanisms of sheets, i.e: bulging and drawing were proposed by Erichsen [18] and Swift [19,20].

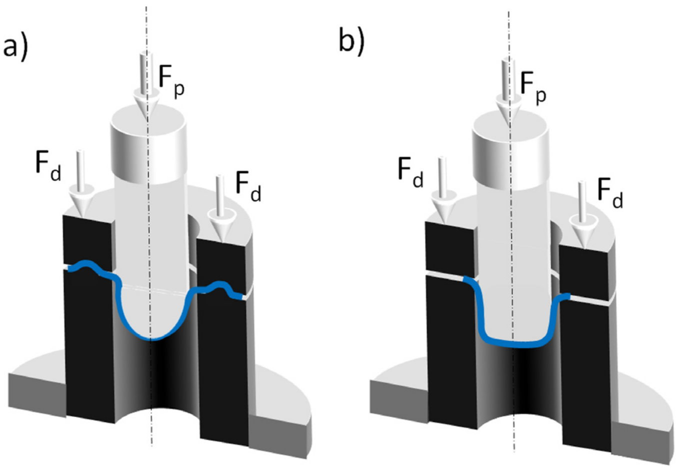

Fig. 1. Scheme of the bulging (a) and drawing (b) processes

The difference in the mechanism of deformation between bulging and drawing generally lies in the fact that in the first case the final height of the cup is obtained by thinning the sheet while the flange is rigidly clamped by blank holder (Fig. 1a) while in the second case sheet metal passes through the rounded edge of the die without any significant sheet metal thinning (Fig. 1b). Different diameters of circular blanks are used in Swift test to find the maximum diameter of the blank (maximum height of a cup) for which the fracture of a cup would not occur.

In the first method proposed by Erichsen, the circular blank fixed rigidly on the periphery by a blank holder is deformed with a metal punch until the appearance of a crack. The cup height determined with this method is defined as the Erichsen index (IE) and is a parameter defining the material formability in specific (from the point of view of friction) bulging conditions (ISO standard 20482: 2013). This test can be carried out on the Erichsen machine shown in Fig. 2a. In this test, a spherical punch and dies with a small radius of the periphery of the hole are used, which significantly reduces the displacement of the material, additionally clamped by the blank holder. In order to carry out the tests for determining the Erichsen index, the tools shown in Fig. 2b have been used.

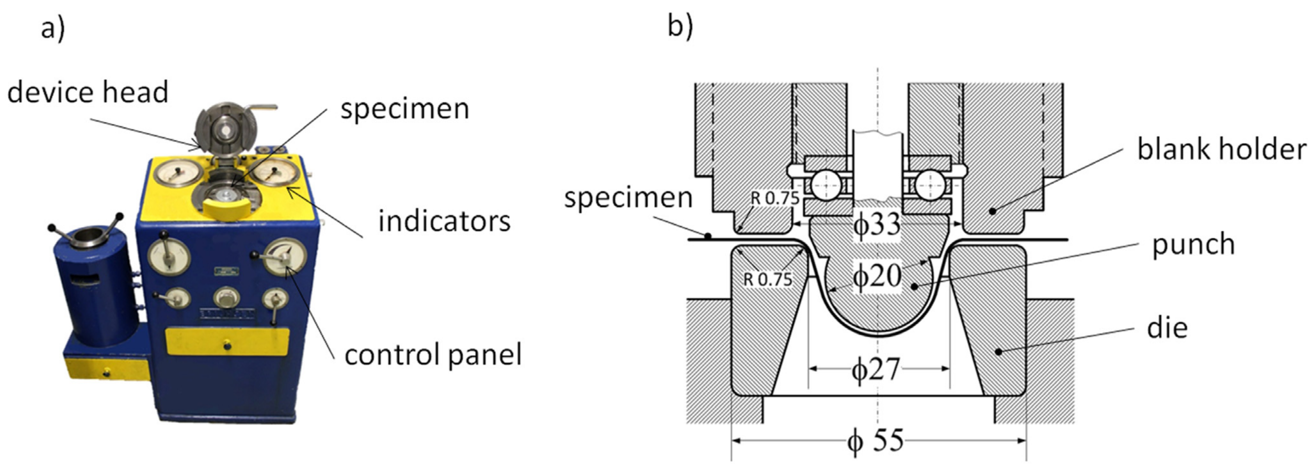

Fig. 2. Presentation of the Erichsen testing method: a) device for bulging; b) schematic cross-section of tools

3. Experimental setup

This paper presents a method that enables observation of specimen surface during bulging on Erichsen testing device. The digital images of deformed specimen are continuously recorded until fracture of specimen occurs. Laser interference phenomenon was used. The rays of coherent light reflected from the rough surface of the specimen interfere with each other creating the so-called laser speckle image (Fig. 3a). This characteristic effect is visible on the recorded surface of the specimen in the form of irregular bright and dark spots. Even the smallest changes in the illuminated surface cause significant changes in the pattern of recorded spots (Fig. 3b). In the proposed method [21], the speckle phenomenon was used to track changes occurring on the surface of a bulged specimen. This makes it possible to detect not only the moment of well visible defects in the form of a groove or a crack, but also the history of deformation that precedes them.

The experimental setup presented in Figure 3c consists of a monochromatic industrial camera with a resolution of 1628×1236 px, 35 mm focal length lens and F16 aperture, 635 nm laser, digital displacement sensor and a computer along with proprietary software dedicated to recording and analysing the speckle images. The camera and the laser are mounted on a specially designed holder that allows the vision system to be placed on a standard Erichsen machine. The design of the machine head allows illumination of the specimen surface with a laser illuminator, as well as the recording of its image using a camera. A very important feature of the speckle effect is that it is independent of the depth of field of the lens, which makes it easier to record the surface moving towards the camera during bulging. The focal length of the lens and the size of the camera matrix have been selected so that they can register the whole working space inside the head. The punch movement is recorded along with the video images, which makes it possible to refer changes in speckle images to the current height of the deformed specimen.

In order to effectively assess the degree of changes in a given area of speckle image, the authors proposed the use of normalized cross-correlation. The arrangement of speckles on two consecutive images divided into blocks of 25×25 pixels is compared. This value was chosen experimentally. The block size should be several times larger than the speckle size, however, too large blocks would reduce the resolution of the analysis. The size of speckles depends mainly on the aperture value. As a result of this operation, values from 0 to 1 are obtained for each block of the image, where 0 is the same arrangement of speckles, and 1 is not similar. Numerical values can be visualized in the form of colours. A graphic visualization of speckle activity has been applied to the photographs shown in Figure 4b. Brighter areas mean higher activity (larger changes in speckle images), while darker areas are places with less activity.

During the Erichsen test, the distribution of speckle activity on the surface of the sheet metal specimen changes considerably. Initially, the entire surface is deformed, and then the deformation gradually disappears from the central part of the sample to its edges. It is visible in the diagrams presented in Fig. 4a, which illustrate the degree of speckle activity in the punch displacement function for three places located at different distances from the specimen axis (A, B and C). The y-axis scale is logarithmic for a better presentation of chart changes. On the basis of the analysis of the rate of disappearance of changes on the surface of the sheet, it is possible to determine the beginning of the local loss of stability N, the formation of groove and crack (a sharp jump in activity). This analysis is carried out on the basis of the average activity (Fig. 4c) of the area (marked with a rectangle in the picture) extending from the axis of the sample to the place where the crack occurred.

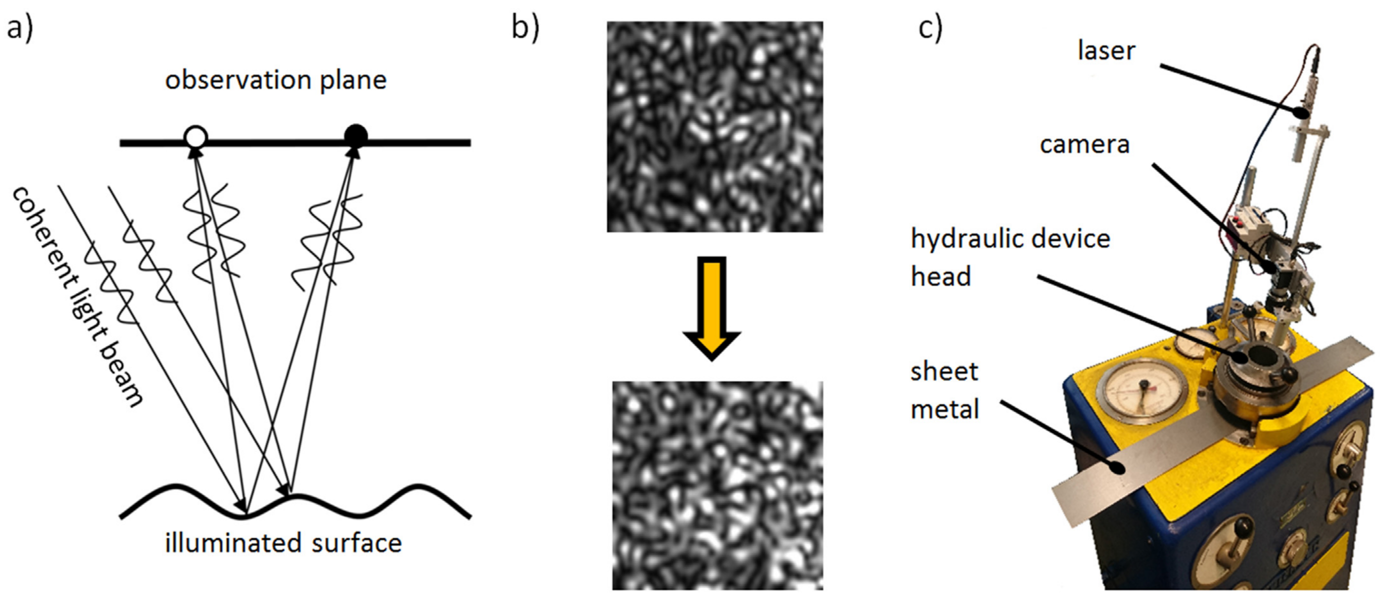

Fig. 3. Principle of the speckle formation (a), changes of the specimen speckle images for two different time moments (b) and the experimental setup (c)

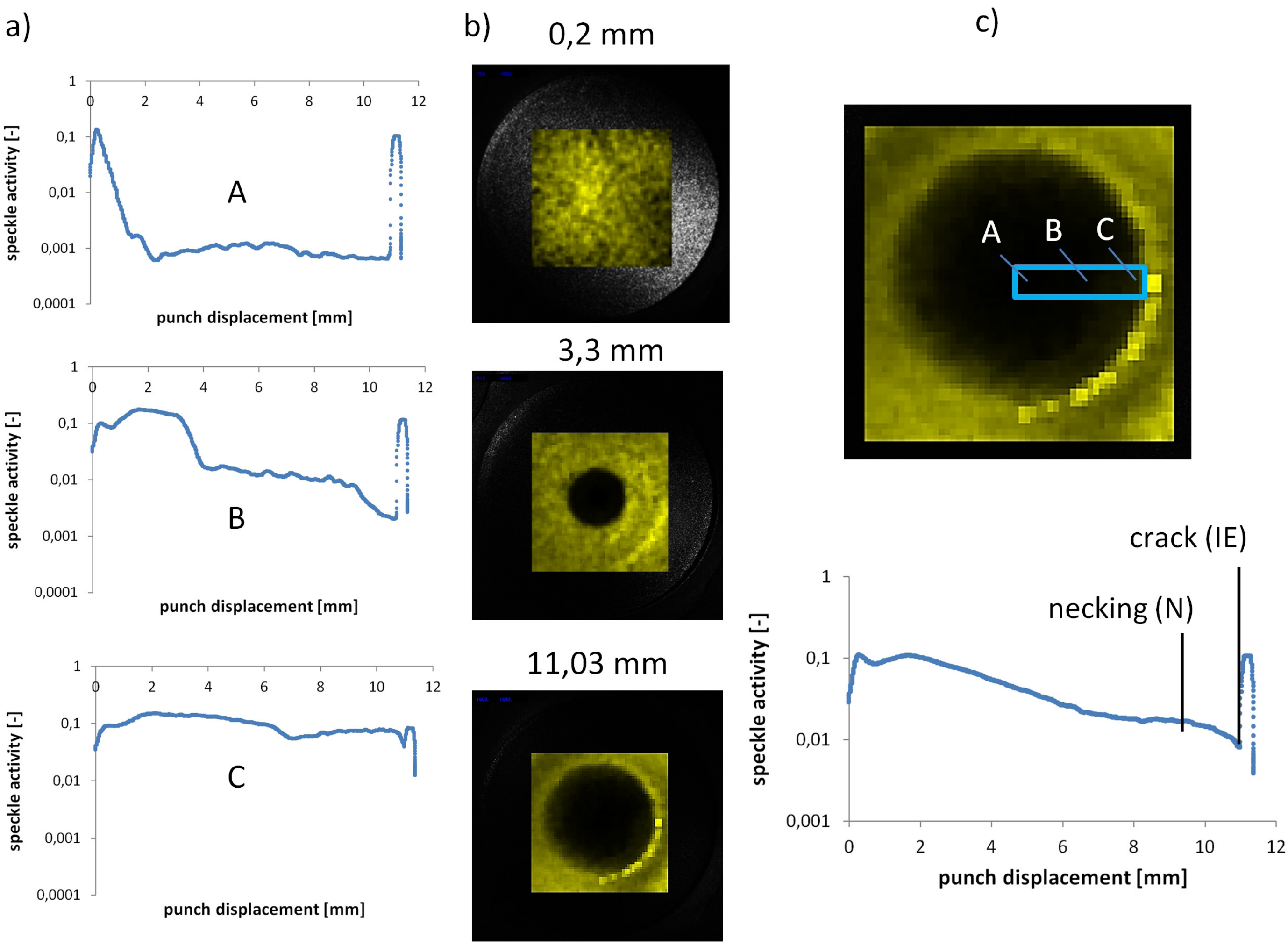

Fig. 4. Analysis of speckle activity during bulging test of the DC01 sheet metal with a thickness of 0.8 mm: a) activity waveforms as a function of punch movement for three different specimen sites A, B and C; b) laser-illuminated specimen surface images with the visualization of the speckle activity for different heights of the sample; c) average speckle activity in the selected area

Data from direct analysis of speckle activity during deformation of DC04 1 mm sample (supplier II, Fig. 5a) are filtered (denoising) by convolution using a rectangular window (Fig. 5b). This window is a low-pass filter. By performing filtration using this window, high frequencies are removed from the data set. High frequencies are responsible for noise in the signal. Removing them makes the data set smoother. A rectangular window is the easiest time window to implement. The width affects the filtration. The larger it is, the smoother is the data set. During filtration the data from the analysis and window values are transferred into the frequency domain using the Fourier transform. Filtration is the multiplication of input data by rectangular window values in the frequency domain. After obtaining the resultant signal, it is subjected to an inverse Fourier transform, thus transferring it again to the time domain. The data obtained after filtration is shown in Fig. 5c, and the collected data with (solid line) and without (dots) filtration from the area marked with a red rectangle in Fig. 5a is shown in Fig. 5d. In Fig. 4 the y-axis scale is logarithmic. However, before filtering, the data itself was subjected to a logarithm operation. Hence $\log_{10}(1) = 0$, $\log_{10}(0.1) = -1$, while for values smaller than 0.1 $\log_{10}$ assumes values below –1.

The emergence of loss of stability causes an increase in speckle activity, which is why the data after filtration should be analysed for dynamics of their DSA changes (Dynamic changes of Speckle Activity) using the Eq. (1):

$$DSA = (y_n - y_{n-1}) - (y_{n-1} - y_{n-2}) \qquad (1)$$

where y is the value of the filtered data set, and n takes the values from 1 to the number of samples of the analysed data set. Using the above formula, DSA is determined and shown in Fig. 6a as a function of punch displacement. A red rectangle indicates the area prior to the crack formation, which is shown enlarged in Fig. 6b. In the central part of Fig. 6a DSA values are oscillating around zero. The amplitude of changes is determined after analysis of this data range. It makes it possible to set limit values for the received data which is shown in the form of blue dotted lines in Fig. 6b. Only when the loss of stability N occurs, there is a sudden change below the limit value. The red point and the vertical line in Fig. 6b indicate initial moment of the loss of stability N.

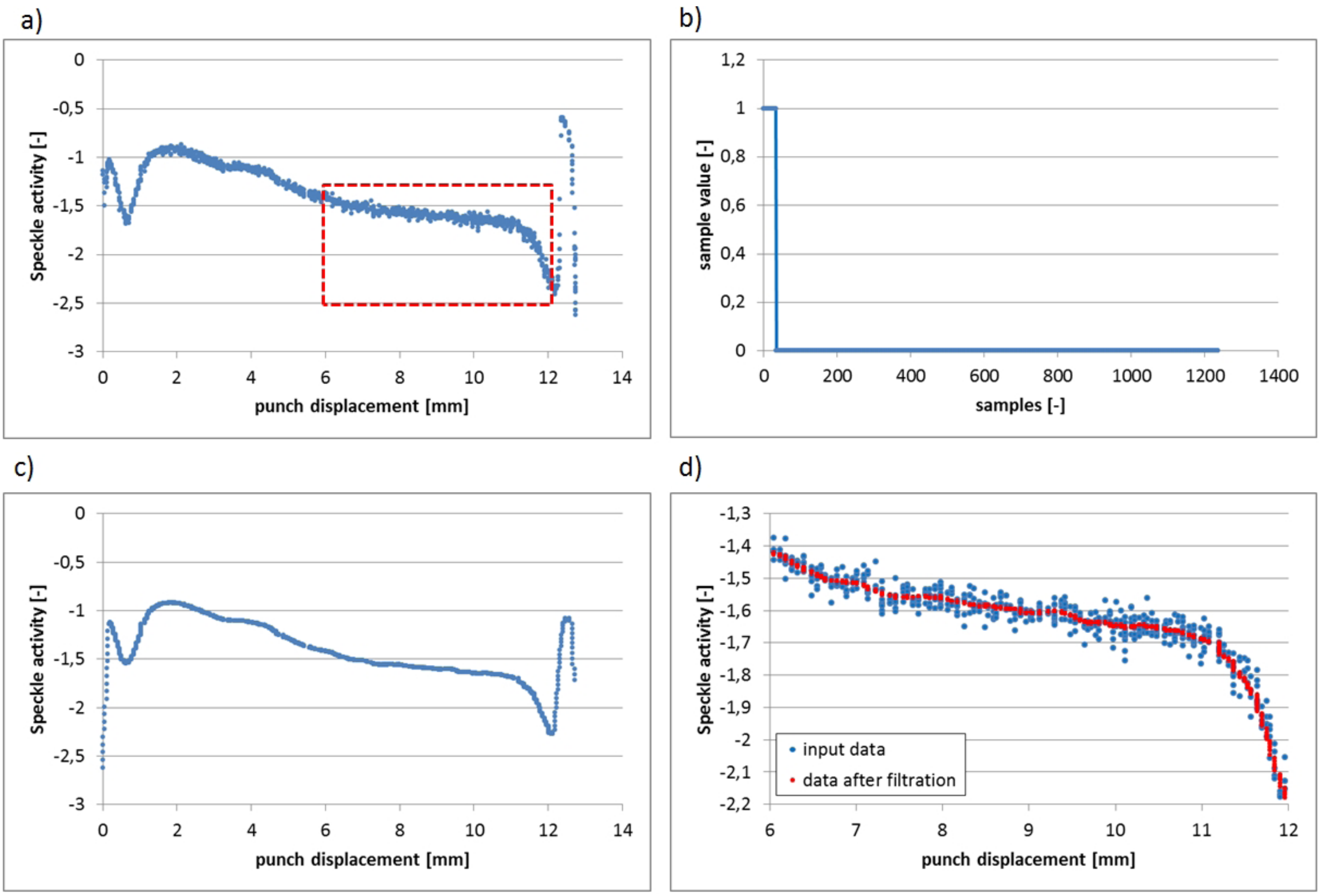

Fig. 5. The process of removing noise from input data: a) input data, b) rectangular window, c) data after filtration, d) summary of input data and data after filtration from the area marked in Fig. 5a

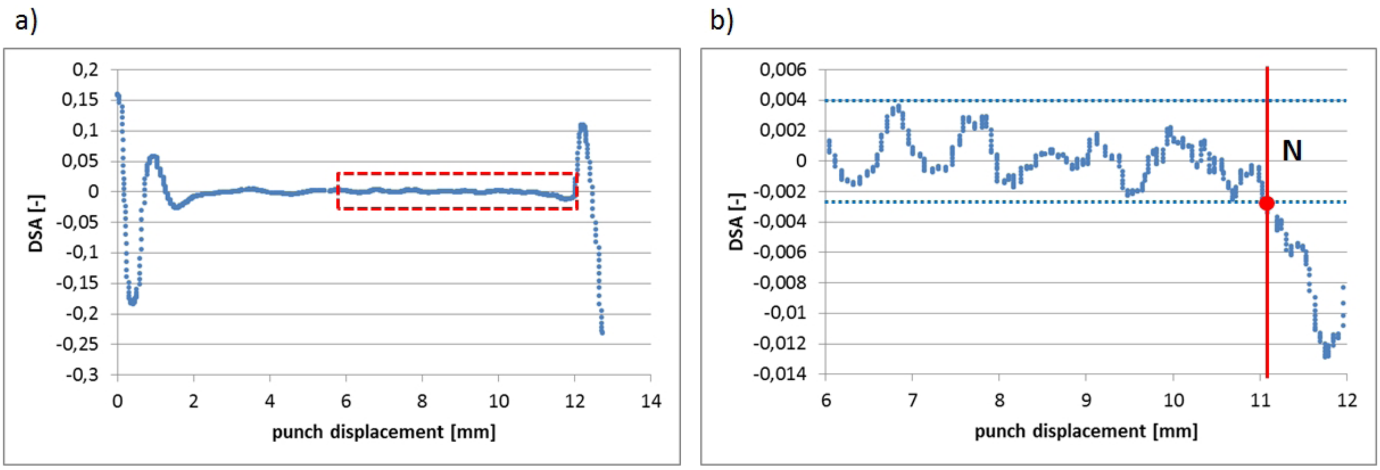

Fig. 6. DSA values as a function of punch displacement (a) and determination of the moment of loss of stability N (b)

4. Results

The tests were carried out for two grades of deep drawing steel sheets DC01 and DC04, commonly used in the automotive industry. The chemical composition and typical mechanical properties are given in Table 1.

DC01 and DC04 steel sheets with a thickness of 0.8 mm were used from supplier I and additionally 1 mm thick DC04

TABLE 1

Mechanical properties and chemical composition of steel sheets in the DC01 and DC04 grades in accordance with EN 10130

Steel sheet grade	R_e [MPa]	R_m [MPa]	A_{80} [%]	C [%] max.	Mn [%] max.	P [%] max.	S [%] max.
DC01	140-280	270-410	min. 28	0.12	0.60	0.045	0.045
DC04	140-210	270-350	min. 38	0.08	0.40	0.030	0.030

steel sheets from two suppliers (supplier I and II). The chemical composition of the sheets used was determined using a Belec In-spect spectrometer and summarized in Table 2. The content of alloying elements C, Mn and P is significantly lower than the maximum permitted in the standard (Table 1), while the S content is only slightly exceeded for DC04 sheet of 1mm thick from supplier II.

TABLE 2

Determined chemical composition of the tested steel sheets

Steel sheet grade and thickness	C [%]	Mn [%]	P [%]	S [%]
DC01 0,8 mm I	0.039	0.26	0.015	0.012
DC04 0,8 mm I	0.034	0.24	0.028	0.011
DC04 1 mm I	0.019	0.205	0.015	0.013
DC04 1 mm II	0.017	0.096	0.006	0.032

Exemplary specimen with bulged areas made during the subsequent Erichsen tests is presented in Fig. 7. The results of finding characteristic defects on the surface of deformed sheet metal obtained using the method based on the speckle effect are presented in Table 3. The table shows Erichsen numbers (IE) for all tested steel sheets. In addition, specimen heights were determined for local loss of stability (N). Based on the measurements made, the difference between the height of the sample at the moment of loss of stability occurrence and occurrence of crack, named in the table as Delta, is determined. In addition, this difference was converted into a percentage in relation to the Erichsen number obtained.

The analysis of Table 3 shows clear differences of results between 1 mm thick DC04 steel sheets from different deliveries. The steel sheet from supplier II not only shows a higher formability (IE and especially N values) but at the same time the difference in the bulged specimen height between loss of stability and cracking (10%) is lower for this sheet compared to the steel sheet from delivery I (up to 22%). As for industrial applications, the steel sheet from supplier II is of course much better than steel sheet from supplier I. What more, N value (height of the bulged specimen) at loss of stability for 1 mm thick DC04 steel sheets from supplier I is surprisingly at the same level as for steel sheets with only 0.8 mm in thickness. This may be related to only slight differences in the properties of the supplied materials.

Fig. 8 shows the courses of speckle activity for selected 1 mm thick DC04 specimens from two different suppliers. In turn, the analyses carried out for steel sheets DC04 and DC01 with a thickness of 0.8 mm did not show any clear differences between the courses of their bulging process.

5. Conclusions

- Quality of the delivered sheet metal is the most uncertain and least recognized area for obtaining input data for computer simulation. Therefore, the authors have drawn attention to the necessity to change the current point of view on description of limiting forming strain and place more attention to new areas of experimental analysis of sheet metal formability with using very well-known Erichsen test.
- A complex methodology and experimental procedure that allows not only to determine the standard Erichsen index but also to follow the material deformation stages immediately preceding the occurrence of the crack have been presented. Accurate determination of these characteristics in the sheet metal forming would be an important application, especially for automotive industry.
- The experimental setup presented in this paper has enabled observation of specimen surface during its bulging on Erich-

Fig. 7. DC04 steel sheet specimen of 1 mm in thickness used for the Erichsen test

TABLE 3

Results obtained using the speckle effect

Sheet metal	DC04 1 mm II			DC04 1 mm I			DC04 0,8 mm I			DC01 0,8 mm I		
Specimen No.	1	2	3	2	3	4	1	2	3	1	2	3
N [mm]	11.2	11.4	10.8	10.1	9.8	9	8.9	9.6	10.3	10.1	10.4	8.6
IE [mm]	12.36	12.28	12.31	11.56	11.42	11.41	11.01	10.94	10.98	10.97	11.08	11.1
N mean [mm]	11.13			9.63			9.6			9.7		
IE mean [mm]	12.32			11.46			10.98			11.05		
Delta [mm]	1.18			1.83			1.38			1.35		
Delta [%]	9.61			15.96			12.54			12.24		

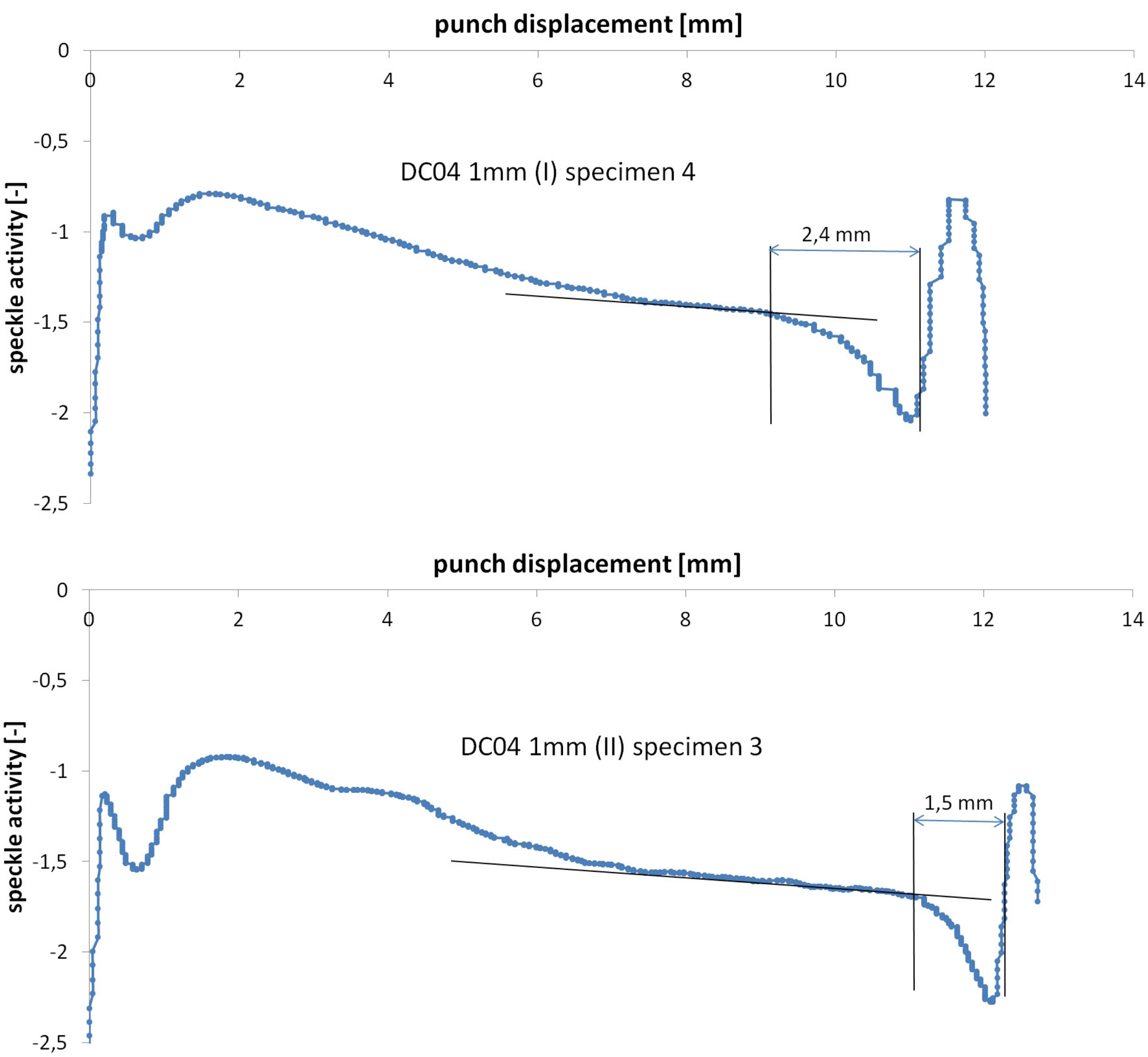

Fig. 8. Comparison of speckle activity patterns for specimen DC04 1 mm supplier I and specimen DC04 1 mm supplier II

sen testing device. The digital images of deformed specimen have been continuously recorded until fracture of specimen occurred. The rays of coherent laser light reflected from the rough surface of the specimen interfered with each other and created the so-called laser speckle images. Changes in speckle images made it possible to detect not only the moment of well visible defects in the form of a groove or a crack, but also the history of deformation that precedes them.

- Extended bulging test results have shown clear differences of results between 1 mm thick DC04 steel sheets from two different deliveries. Both Erichsen index IE as well as height of bulged specimen N at loss of stability of sheet metal were much higher for one delivery as comparing with the other. Hence, it has been proved that knowing the grade of steel sheet and determination of only the Erichsen index is not sufficient for quantitative evaluation of formability.
- Presented experimental setup enabling relatively simple as well as accurate determination of the N value should be helpful in avoiding of product defects in sheet metal forming.
- A new approach presented in the paper provides new opportunities in better understanding of the Erichsen index in combination with the material deformation history.

REFERENCES

[1] A. Mohsen, B.A. Mohamed, C. Chaker, D. Fakhreddine, Adv. Prod. Eng. Manag. **3** (2), 81-92 (2008).

[2] Y. Song, L. Hua, Procedia Engineer. **81**, 730-735 (2014).

[3] G. Giuliano, F. Samani, Appl. Mech. Mater. **365-366**, 425-428 (2013).

[4] S.U. Sunil, K.B. Pai, IOSR Journal of Mechanical and Civil Engineering **11**, 52-55 (2014).

[5] T. Animesh, R.C. Vinit, M. Kapish, V. Mukul, J. Athar, K.S. Mohit, Journal on Material Science **1**, 14-18 (2013).

[6] Y. Ishida, F. Hatashita, Calsonic Kansei Technical Review **12**, 23-28 (2016).

[7] R.N. Reddy, S. Theja, G. Tilak, The SIJ Transactions on Industrial, Financial & Business Management **1** (2), 52-57 (2013).

[8] F.S. Sorce, S. Ngo, C. Lowe, A.C. Taylor, J. Mater. Sci. **54**, 7997-8009 (2019).

[9] I. Kacar, F. Ozturk, F. Jarrar, Journal of Modern Mechanical Engineering and Technology **1**, 68-74 (2014).

[10] A. Andersson, AIP Conference Proceedings, 778. Melville, NY: American Institute of Physics, 113-118 (2005).

[11] E. Fuente-Lopez, F. M.l Trespaderne, Lect. Notes. Comput. Sc. **5815**, 345-353 (2019).

[12] W. Boesemann, R. Godding, H. Huette, International Archives of Photogrammetry and Remote Sensing **33**, 48-55 (2000).

[13] A. Zoescha, T. Wiener, M. Kuhlb, Proc. CIRP. **33**, 179-184 (2015).

[14] T. Giesko, A. Zbrowski, P. Czajka, Problemy Eksploatacji **1**, 97-108 (2007) (in Polish).

[15] T. Chezan, T. Khandeparkar, J. van Beeck, M.Sigvant, Journal of Physics: Conference Series **1063**, 1-6 (2018).

[16] C. Jaremenko, N. Ravikumar, E. Affronti, M. Merklein, A. Maier, Determination of Forming Limits in Sheet Metal Forming Using Deep Learning. Materials **12** (1051), 1-17 (2019).

[17] D. Banabic, Sheet metal forming processes: Constitutive modelling and numerical simulation, Springer-Verlag, Berlin Heidelberg (2010).

[18] A.M. Erichsen, Stahl und Eisen. **34**, 879-882 (1914) (in German).

[19] S.Y. Chung, H.W. Swift, P. I. Mech. Eng. **165**, 199-223 (1951).

[20] H.W. Swift , Sheet Metal Industries **31**, 817-828 (1954).

[21] A. Kocańda, C. Jasiński, Arch. Civ. Mech. Eng. **16**, 211-216 (2016).