Publishing House
AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE

Informatyka w Technologii Materiałów

Vol. 13, 2013, No. 1

EFFECT OF FRICTION ON FAILURE LOCATION IN SHEET METAL FORMABILITY TESTS

DMYTRO LUMELSKYY[1]*, IZABELAMARCZEWSKA[1], JERZY ROJEK[1], RYSZARD PĘCHERSKI[1], FRANCISZEK GROSMAN[2], MAREK TKOCZ[2]

[1] Institute of Fundamental Technological Research, Polish Academy of Sciences, Pawińskiego 5B, 02-106Warsaw, Poland
[2] Silesian University of Technology, Krasińskiego 8, 40-019 Katowice, Poland
**Corresponding author: dlumelsk@ippt.gov.pl*

Abstract

This paper presents numerical investigations of the influence of friction on sheet deformation in Nakazima type formability tests. Numerical simulations have been performed using the authors' own explicit dynamic finite element program. Numerical results have been compared with experimental data. Location of fracture was of major interest in this work. The studies confirmed that the fracture location near the center of the specimen as required by the standards can be obtained for low values of the friction coefficient. Numerical simulation combined with the inverse analysis has been used to estimate a real value of the friction coefficient in the Nakazima formability test.

Key words: formability test, explicit FE method, friction, fracture location

1. INTRODUCTION

Formability of metal sheets is studied experimentally using various tests, including uniaxial tensile test, hydraulic bulging test, and different punch stretching methods such as Erichsen (20482, 2003), Nakazima (12004-2, 2008) or Marciniak (12004-2, 2008) tests. Formability tests allow generation of forming limit curves (FLC) defining safe forming conditions in terms of principal strains. Punch stretching tests consist in stretching of a sheet specimen by means of a punch until occurrence of fracture. Taking different specimen geometries different strain paths can be obtained. Friction, and in general, tribological conditions of contact between the tools and sheet, affect very much the results of formability tests. Friction changes strain paths and failure location in sheet specimen.

The FLC should be determined by proportionally straining the material producing linear strain paths. Friction, affecting strain paths in a tested specimen, is usually undesired phenomenon in formability tests (Abspoel et al., 2011), therefore different measures are taken to reduce friction. In the Nakazima tests, either oil, grease or polymer foils should be used as lubricant systems (12004-2, 2008). Tribological conditions should be adjusted so that fracture occurs within a distance less than 15% of the punch diameter away from the apex of the dome. Zero friction would allow us to obtain fracture at the center of specimen with nearly strain path at fracture point. The failure location is very sensitive to friction. Even small friction increase displaces the location of fracture (Larsson et al., 2007).

The aim of this study is to develop a numerical model allowing us to identify frictional conditions in

ISSN 1641-8581

a selected case of the Nakazima test and study numerically effect of change of friction on strain distribution and failure location in a sheet specimen.

2. EXPERIMENTAL STUDIES

Nakazima type formability tests have been carried out for the steel grade DC04 1 mm thick. Figure 1 shows the geometry of the tools and specimens used in the tests. Use of specimens of different widths allows us to obtain failure for different strain paths. Figure 2 presents a circular specimen with a fracture after the testing, which will be studied numerically. This test has been performed without additional lubricant which has lead to the fracture nearly 20mmoff-set from the centre. This is equivalent to 26% of the punch diameter. The fracture location does not satisfy the requirements of the standard (12004-2, 2008), nevertheless, it is a suitable test case for numerical studies. The objective of the numerical simulations has been to identify the friction value in the test and study its effect on the location of fracture.

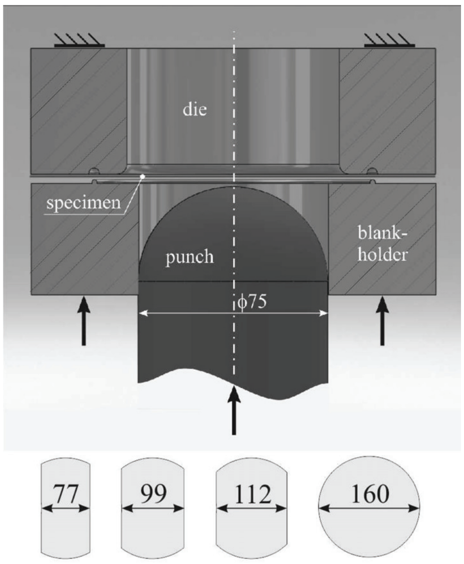

Fig. 1. Schematic representation of tools and specimens for formability tests.

1. NUMERICAL MODEL

A numerical model allowing us to simulate the formability tests has been developed. Numerical analyses have been performed using the authors' own computer explicit dynamic finite element developed within a framework of the project Numpress (NUMPRESS, 2012). Sheet was discretized with a linear shell triangular elements BST (Rojek & Onate, 1999; Rojek et al., 2001). The material has been considered assuming the Hill'48 model (Hill, 1948). Mechanical properties determined be means of the uniaxial tension tests are given in table 1. The tools have been modelled as rigid bodies whose surfaces has been discretized with triangular facets. Frictional contact between the tool and sheet has been treated using the Coulomb model of friction. Deformation process has been analysed under prescribed motion of the punch.

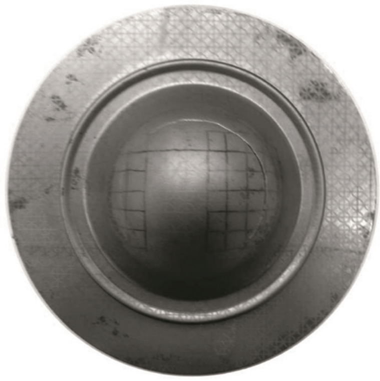

Fig. 2. Fractured circular specimen after testing.

From the analysis of the full model with exact representation of the drawbead geometry, it was found out that the drawbead nearly completely blocks the flow of the sheet (Lumelskyy et al., 2012). Therefore, in this work, simulations were carried out using a simplified model, in which we considered a part of the sheet within the drawbead line with a restricted motion of the sheet along the drawbead line. This allowed us to reduce considerably the number of elements and to avoid very small elements limiting the time step length.

Table 1. Properties of the tested DC04 steel sheet.

Direction of the sample	C [MPa]	n for ε_i =0.02÷0.20	r
0°	498	0.26	1.7
45°	506	0.22	1.3
90°	532	0.26	1.8

4. NUMERICAL RESULTS

The effect of friction on the location of fracture is demonstrated in figure 3 showing distribution of sheet thickness in the deformed circular specimen obtained in simulations assuming zero friction (figure 3a) and friction characterized by the Coulomb coefficient 0.3 (figure 3b). In the frictionless case, maximum thinning, indicating a possible fracture, is obtained at the center of the blank, while in the case with non-zero friction the area of diffused necking is displaced from the centre by a certain distance. This displacement agrees with observations made by other authors (Knibloe &Wagoner, 1989; Silva et al., 2010).

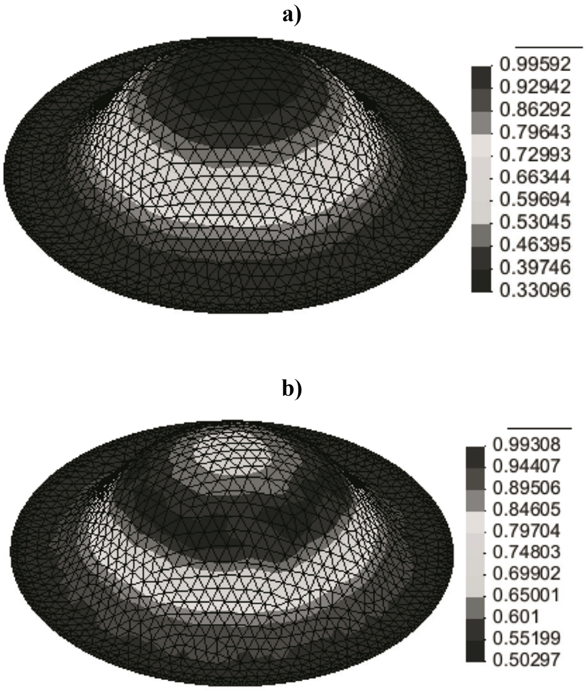

Fig. 3. *Simulated distribution of sheet thickness in the stamped circular specimen: a) without friction, b) with friction.*

Accurate prediction of experimental results shown in figure 2 requires knowledge of the real friction conditions. Identification of unknown friction model parameters in metal sheet forming can be carried out by means of inverse analysis (Szeliga et al., 2006; Li et al., 2010; Silva et al., 2010). In the inverse analysis, the identification of unknown model parameters **x** is performed by searching a minimum of the objective (or cost) function, defined as the difference between the calculated d_{ci} output response and measured in experiment d_{mi} output response as

$$\Phi(\mathbf{x}) = \sqrt{\sum_{i=1}^{n} \beta_i \left(d_i^c(\mathbf{x}) - d_i^m \right)^2} \qquad (1)$$

where n denotes the number of measurement points and β_i are the weight factors (Szeliga et al., 2004; Szyndler et al., 2001). In this work, the minimization will be performed with respect to the Coulomb friction coefficient, i.e. $\mathbf{x} = \{\mu\}$, and principal strains ε along the specimen radius will be taken as the representative results for the model calibration. Two types of cost functions will used. In the first case, the cost function is defined as

$$\Phi_1(\mu) = \sqrt{\sum_{i=1}^{n} \left(\varepsilon_i^c(\mu) - \varepsilon_i^m \right)^2} \qquad (2)$$

where $\varepsilon_i^c(\mu)$ and ε_i^m denote the calculated and measured strain values in a selected point along the radius, respectively.

The alternative cost function is based on the difference between localization of the peaks of experimentally measured and numerical strain curves, r_{max}^m and r_{max}^c, respectively

$$\Phi_2(\mu) = \sqrt{\left(\frac{(r_{max}^c(\mu) - r_{max}^m}{r_{max}^m} \right)^2} \qquad (3)$$

The optimization problem resulting from the inverse analysis has been solved by direct search. The problem has been searched for a set of values of the friction coefficient from the interval (0,0.3). The distributions of the principal strains obtained for different values of the friction coefficient are plotted in figure 4. Numerical strain distributions are compared with experimental results. The effect of varying friction coefficient on the strain distribution can be clearly observed. With zero friction, the maximum of the major true strain occurs in the central region of the test specimen, gradually decreasing up to the region of contact with the die. With the increase of the friction coefficient, the major strain distribution in the center decreases and the peak is displaced further from the center. The distribution of minor strains is more homogenous and is less affected by change of the friction coefficient. The distribution of the thickness strain is correlated with the distribution of the major strain.

Taking the numerical and experimental results presented in figure 4 the cost functions have been calculated for different friction coefficients according to equations (2) and (3). The calculated cost functions are plotted as functions of the friction coefficient in figure 5. The cost function Φ_1 has been calculated for the three major principal strains, while the function Φ_2 has been evaluated for the major and thickness strains, since the curves of the minor principal strain distributions (figure 4c) do not have peaks. The cost function Φ_1 evaluated for the major principal strain has minimum for the friction coefficient $\mu \in (0.175,0.2)$, while the same cost function evaluated for the thickness strain has minimum for $\mu = 0.225$. This means that the respective strain distributions fit best experimental results (see figure 4).

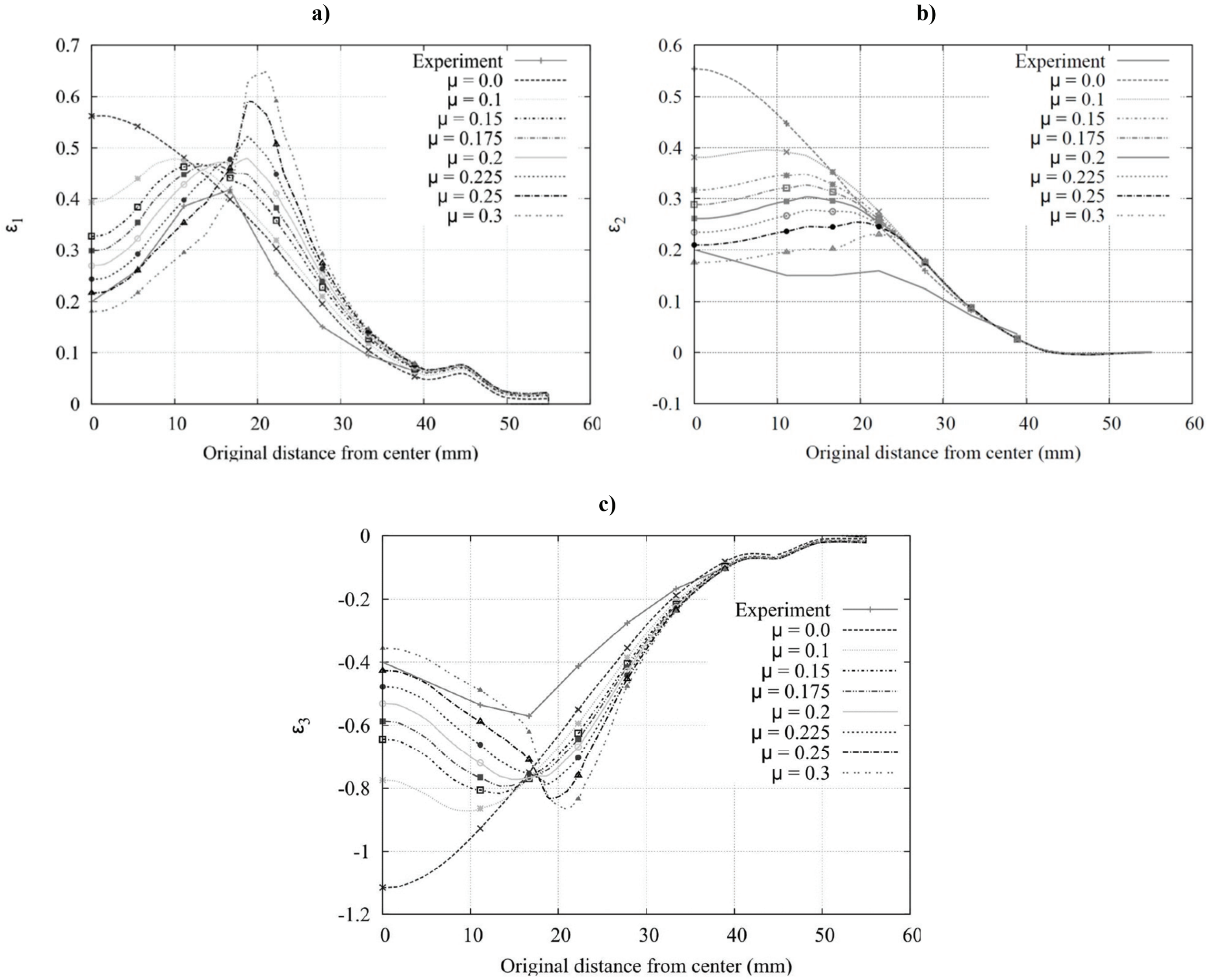

Fig. 4. Distribution of principal strains along the radius: a) major principal strain, b) minor principal strain, c) thickness strain.

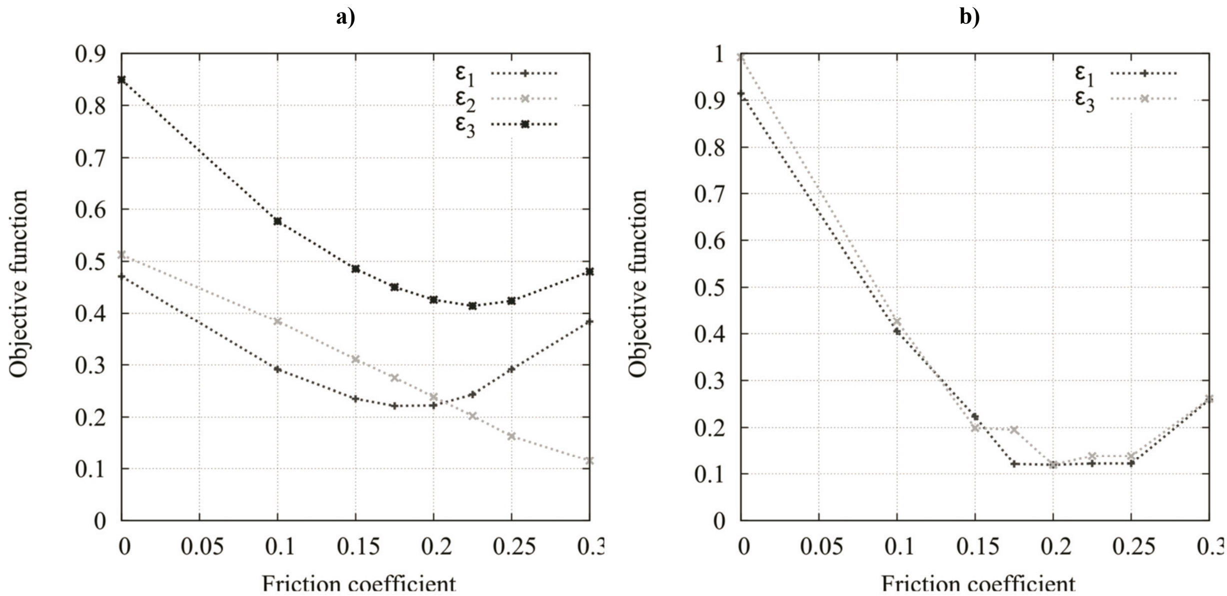

Fig. 5. Objective functions for different strain components: a) objective function based on curve fitting, b) Objective function based on the distance between peaks.

This means that the real friction coefficient should be contained in the interval (0.175, 0.225). The cost function Φ_2 does not yield the unique value of the friction coefficient, either. From the curves plotted in figure 5, we can estimate the friction coefficient is contained in the 5 interval (0.175,0.25).

The effect of friction can also be shown in forming limit diagrams (FLD). Figure 6 shows the FLD for different values of the friction coefficient. The points corresponding to the local strains are confronted with the forming limit curve (FLC) and the experimental strains. Frictionless bulging would produce a straight strain path in biaxial tension. With increase of friction, the strain path departs from the biaxial tension. This effect was reproduced in the numerical simulation. The numerical strains for μ = 0.3 correlate best with the experimental ones. It may indicate that the true friction coefficient is close to this value.

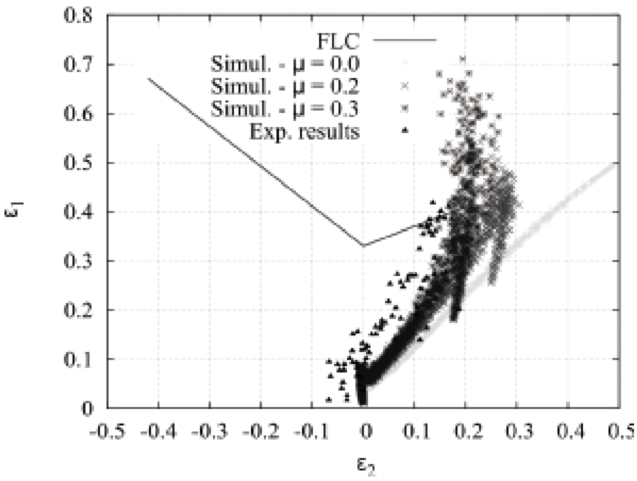

Fig. 6. *Comparison of experimental and numerical distributions of local strains for different friction coefficients.*

5. CONCLUSIONS

Numerical simulations have shown that specimen deformation in Nakazima type formability tests strongly depends on friction between the punch and sheet. Friction between the punch and sheet influences the strain path and location of fracture. Location of fracture close to the center of the specimen as required by the standards can be achieved only for low values of the friction coefficient. With the increase of the friction coefficient the fracture is displaced further from the center. Effective friction coefficient at formability tests is difficult to be measured experimentally. It can be determined by the inverse analysis based on fitting numerical strain distribution to that observed in experiments.

Acknowledgements. The authors acknowledge funding from: (1) European Regional Development Fund within the framework of the Innovative Economy Program, project number POIG.01.03.01-14-209/09, acronym – NUMPRESS, (2) Ministry of Science and Higher Education through research project NN501 1215 36, (3)National Science Centre through research project No. 2311/B/T02/2011/40.

REFERENCES

12004-2, ISO, 2008, *Metallic materials – Sheet and strip – Determination of forming-limit curves. Part 2: Determination of forming-limit curves in the laboratory*.

20482, ISO, 2003,*Metallic materials – Sheet and strip – Erichsen cupping test*.

Abspoel, M., Atzema, E.H., Droog, J.M.M., Khandeparkar, T., Scholting, M.E., Schouten, F.J., Vegter, H., 2011, Inherent influence of strain path in Nakazima FLC tests, *Proceedings of the 8th IDDRG Conference*, Mumbai, India.

Hill, R., 1948, A theory of the yielding and plastic flow of anisotropic metals, *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, volume 193, 281-297.

Knibloe, J.R., Wagoner, R., 1989, Experimental investigation and finite element modeling of hemispherically stretched steel sheet, *Metallurgical Transactions A*, 20A, 1509-1521.

Li, Y., Luo, M., Gerlach, J., Wierzbicki, T., 2010, Prediction of shear-induced fracture in sheet metal forming, *Journal ofMaterials Processing Technology*, 210, 1858–1869.

Lumelskyy, D., Rojek, J., Pecherski, R., Grosman, F., Tkocz,M., 2012, Numerical simulation of formability tests of pre-deformed steel blanks, *Archives of Civil and Mechanical Engineering*, 12, 133–141.

Larsson, M., Mattiasson, K., Sigvant, M., 2007, Some observations on failure prediction in sheet metal forming, *Proceedings of the 6th European LS-DYNA Users' Conference*, 5.93-5.102.

NUMPRESS, 2012, *Advanced methods of analysis, optimization and reliability for industrial processes of metal sheet stamping. Innovative Economy Program, project number POIG.01.03.01-14-209/09*. IPPT, http://numpress.ippt.gov.pl/.

Rojek, J., Onate, E., 1999, Sheet springback analysis using a simple shell triangle with translational degrees of freedom only, *Int. Journal of Forming Processes*, 1, 75-296.

Rojek, J., Zienkiewicz, O. C., Onate, E., Postek, E., 2001, Advances in FE explicit formulation for simulation of metalforming processes, *Journal of Materials Processing Technology*, 119, 41-47.

Silva, H.C., Lajarin, S.F.,Marcondes, P.V.P., 2010, Analysis of numerically simulated true strain on high stampability sheets, *J. of the Braz. Soc. of Mech. Sci. and Eng.*, XXXII, 21-27.

Szeliga, D., Gawad, J., Pietrzyk, M., 2004, Parameters identification of material models based on inverse analysis, *Int. J. Appl. Math. Comput. Sci.*, 14, 549-556.

Szeliga, D., Gawad, J., Pietrzyk,M., 2006, Inverse analysis for identification of rheological and friction models in metal forming, *Computer Methods in Applied Mechanics and Engineering*, 195, 6778-6798.

Szyndler, D., Pietrzyk, M., Hodgson, P.D., 2001, Identification of parameters in the internal variable constitutive model and friction model for hot forming of steels. *Proc. NUMIFORM'2001*, eds, Mori, K., Toyohashi, Japan, 285-290.

WPŁYW TARCIA NA POŁOŻENIE MIEJSCA PĘKANIA BLACHY W PRÓBACH TŁOCZNOŚCI

Streszczenie

Artykuł przedstawia analizę numeryczną wpływu tarcia na rozkład odkształceń w próbie tłoczności metodą Nakazimy. Symulacje numeryczne zostały przeprowadzone w autorskim programie metody elementów skończonych z jawnym całkowaniem ruchu względem czasu. Wyniki numeryczne porównano z danymi eksperymentalnymi. Główną uwagę zwrócono na położenie miejsca pęknięcia. Badania potwierdziły, że miejsce pęknięcia w pobliżu środka próbki zgodnie z wymaganiami norm można uzyskać przy niskich wartościach współczynnika tarcia. Symulacja numeryczna w połączeniu z analizą odwrotną została wykorzystana do oszacowania rzeczywistej wartości współczynnika tarcia w przeprowadzonych próbach tłoczności metodą Nakazimy.

Received: September 20, 2012
Received in a revised form: November 4, 2012
Accepted: November 21, 2012