23rd International Conference
ENGINEERING MECHANICS 2017
Svratka, Czech Republic, 15 – 18 May 2017

SIMULATION OF THE SMALL PUNCH TEST OF AISI 316L AUSTENITIC STEEL

P. Kubík*, J. Petruška, J. Hůlka***, F. Šebek*****

Abstract: *Present paper deals with numerical simulation of the small punch test of austenitic stainless steel, AISI 316L, which is often used in the nuclear industry. In order to model the plastic material behavior, the well-known von Mises yield criterion with isotropic hardening and associated flow rule was adopted. The ductile fracture was modeled using two widespread ductile fracture criteria which were calibrated using various fracture tests. The whole material model was implemented into the explicit finite element code using the user subroutine of Abaqus/Explicit commercial software. The results were compared to those obtained experimentally.*

Keywords: Small punch test, AISI 316L, Multi-linear material model, Ductile fracture, Element deletion technique.

1. Introduction

The Small Punch Test (SPT) was developed by Manahan et al. (1981) for assessment of actual mechanical properties of irradiated materials in the beginning of the nineties. Its great advantage is a very small dimension of the testing specimen which allows to extract a small amount of material from the structure. Most of the properties such as yield stress, ultimate tensile strength, creep behavior or ductility are obtained on the basis of empirical correlation or numerical simulation (Abendroth and Kuna, 2003).

The disk-shaped specimen is mounted between the upper and lower dies and then it is punched using the piston with hemispherical end or using a ball which is placed between the piston and specimen (Rouse et al., 2013). The illustration of SPT apparatus is in Fig. 1 together with important dimensions and description of particular components.

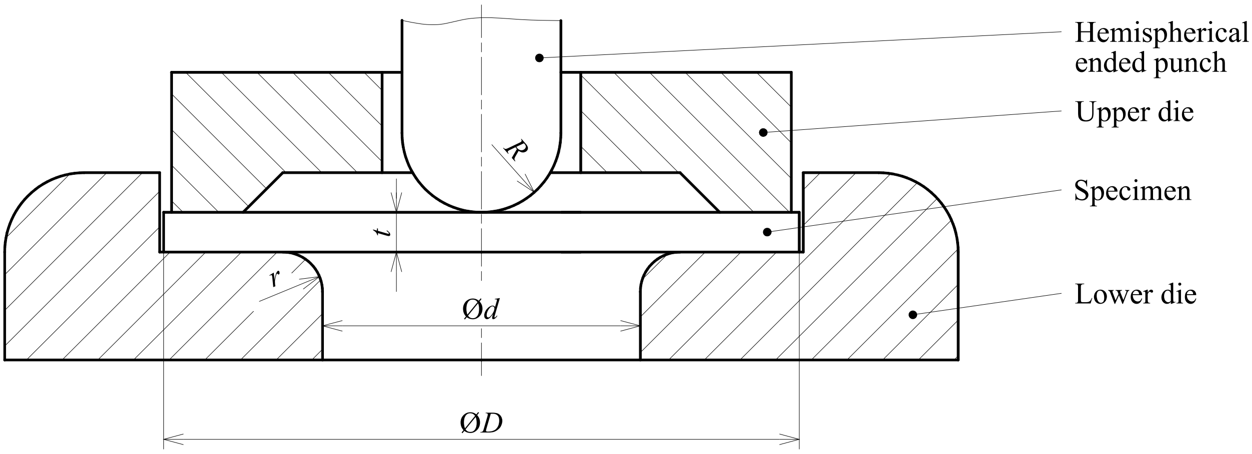

Fig. 1: Schematic drawing of SPT apparatus.

* Ing. Petr Kubík, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, kubik.p@fme.vutbr.cz

** Prof. Ing. Jindřich Petruška, Ph.D.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, petruska@fme.vutbr.cz

*** Ing. Jiří Hůlka, PhD.: Institute of Applied Mechanics; Resslova 972/3; 602 00 Brno; CZ, hulkaj@uam.cz

**** Ing. František Šebek, PhD.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Faculty of Mechanical Engineering, Brno University of Technology; Technická 2896/2; 616 69, Brno; CZ, sebek@fme.vutbr.cz

2. Experimental program

All tested specimens were manufactured from the cold-rolled plate with 400 × 300 × 20 mm. The specimens' axes were coincident with the rolling direction.

Tensile tests of smooth cylindrical specimen with 8 mm diameter and 40 mm gauge length and notched cylindrical specimens with 1.2, 2.5 and 5 mm notch radii were performed. The smallest diameter of the notched cylindrical specimens was 6 mm and the gauge length was 30 mm. All mentioned tests were repeated twice.

Another specimen geometry was a notched tube with 7 mm inner diameter and 14 mm outer diameter. The notch with 3 mm radius was on the diameter of 9 mm. These specimens were loaded by a combination of a tension and torsion. The ratios of axial displacement and twist angle were 0, 1 and ∞ mm/rad. There were done always two tests for each of three ratios.

The upsetting tests of six cylinders with a spherical recess of 5 mm radius were carried out (Kubík et al., 2016). The height and diameter of the cylinders were both 10 mm.

The disk with D = 8 mm diameter and t = 0.5 ± 0.005 mm thickness was used for SPT. It was punched using a piston with hemispherical end of R = 1 mm radius. The fillet radius of lower die was r = 0.5 mm. Four tests were executed without using any lubrication between the contact pairs. The crack was initiated on the radius of 1.05 mm. Then, it propagated tangentially along the circumference until the spherical cap was folded out (Fig. 4).

3. Calibration of material models

The classical von Mises plasticity with isotopic hardening and associated flow rule, used in various applications (Petruška et al., 2012, 2016), were chosen for the description of material behavior. The flow curve was identified using a tensile test of smooth cylindrical specimen in multi-linear form (Kubík et al., 2011). Then, the curve was approximated using Hollomon hardening law in the following form

$$\bar{\sigma} = K\bar{\varepsilon}^{n} \tag{1}$$

where $\bar{\sigma}$ is the equivalent stress, K = 1529.7 MPa is the strength coefficient, $\bar{\varepsilon}$ is the total strain and n = 0.4858 is the strain hardening exponent.

The ductile fracture was simulated using two chosen phenomenological criteria. The first one was the four-parametric, $F_1,\dots,F_4$, Xue–Wierzbicki model (Wierzbicki et al., 2005). The fracture strain is dependent on the stress triaxiality η and normalized third invariant of deviatoric stress tensor ξ as

$$\bar{\varepsilon}^{f}_{XW} = F_1 \mathrm{e}^{-F_2\eta} - \left(F_1 \mathrm{e}^{-F_2\eta} - F_3 \mathrm{e}^{-F_4\eta}\right)\left(1-|\xi|^{\frac{1}{n}}\right)^{n} \tag{2}$$

The second was the modified Bai–Wierzbicki model (Španiel et al., 2014). Here, the fracture strain is not symmetric with respect to the normalized Lode angle

$$\bar{\varepsilon}^{f}_{MBW} = \left(\frac{1}{2}\left(N_1 \mathrm{e}^{-N_2\eta} + N_5 \mathrm{e}^{-N_6\eta}\right) - N_3 \mathrm{e}^{-N_4\eta}\right)\bar{\theta}^{4} + \frac{1}{2}\left(N_1 \mathrm{e}^{-N_2\eta} - N_5 \mathrm{e}^{-N_6\eta}\right)\bar{\theta} + N_3 \mathrm{e}^{-N_4\eta} \tag{3}$$

where $\bar{\theta}$ is the normalized Lode angle and $N_1,\dots,N_6$ are the material constants.

Numerical simulations of experiments were conducted in order to obtain the state variables ξ, $\bar{\theta}$ and η which enter the calibration and are not directly measurable. The geometry in Abaqus/Standard was discretized using 4-node CAX4R elements with reduced integration. Elements with the size of 0.075 mm were applied within the gauge lengths in order to eliminate the size effect. The state variables evolutions were obtained from the crack initiation loci (Abbassi et al., 2013).

All experiments mentioned in Chapter 2 except of the small punch tests were used for ductile fracture criteria calibration. The identification was carried out in the MATLAB R2015a software. Fracture envelopes of respective criteria are in Fig. 2 where the red circles correspond to the tensile tests of smooth and notched cylindrical specimens, black squares represent the biaxial tests of notched tubes and the blue diamond shows the position of the upsetting test of a cylinder with a specific recess.

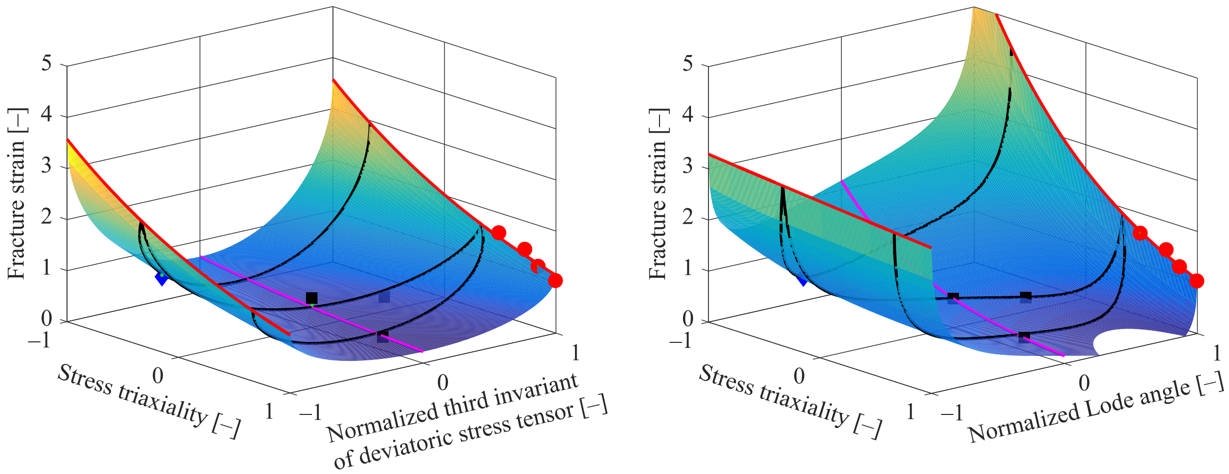

Fig. 2: Fracture envelope of Xue–Wierzbicki (left) and modified Bai–Wierzbicki (right) model.

4. Simulations of SPT

The spatial model of SPT was realized. The specimen was discretized by 8-node C3D8R elements with reduced integration. Central part of the specimen was discretized using the fine mesh with elements of 0.075 mm. Tools were modeled as analytical rigid surfaces and discretized by special ARSR elements. The friction coefficient was taken 0.1 as it is usual for the steel-to-steel contacts with no lubrication.

Both ductile fracture criteria were implemented using Vectorized User MATerial (VUMAT) within the Abaqus finite element software. VUMAT and explicit finite element method are suitable for dynamic processes (Peč et al., 2016), non-linear problems or ductile fracture simulations (Šebek et al., 2014). The ductile fracture initiation and propagation were realized through the element deletion technique.

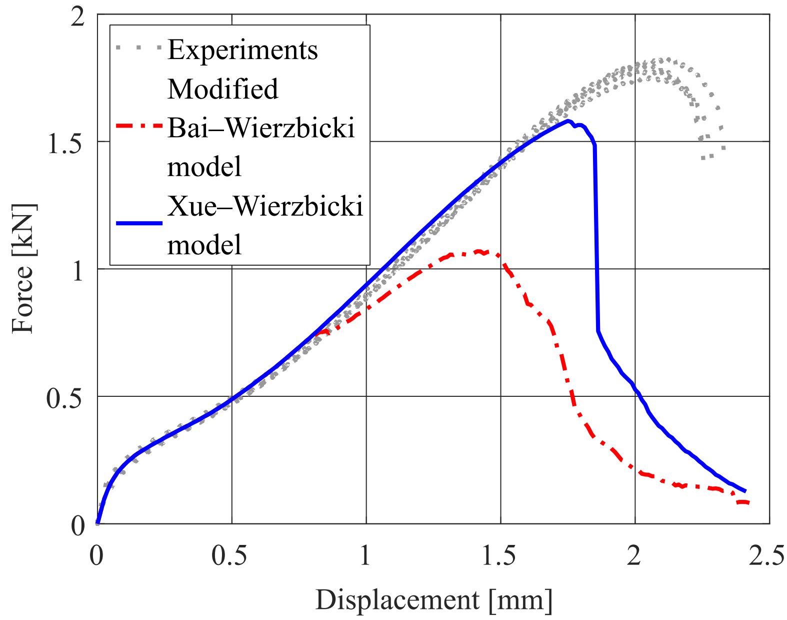

Fig. 3: Force–displacement responses from experiments and numerical simulations of SPT.

Force–displacement responses from the experiment together with those obtained computationally using particular criteria are in Fig. 3. Good result was achieved with Xue–Wierzbicki model which predicted the rupture slightly earlier than in experiment. The crack initiation was on the diameter of 0.55 mm, which increased during loading (it is 1.08 mm in Fig. 4). Modified Bai–Wierzbicki model predicted the ductile fracture wrongly. The initiation was too early and on the diameter where the fillet radius of lower die was situated. This situation was more close to blanking of circular holes, which is in contradiction with current experiment. The comparison between experimental observation and predictions of crack propagation is in Fig. 4, where there are damage contours represented by a rainbow colors. The blue color corresponds to a virgin material without any damage and the red color to exhaustion of load-carrying capacity. The grey color represents a negative value which is physically unrealistic (Kubík et al., 2014).

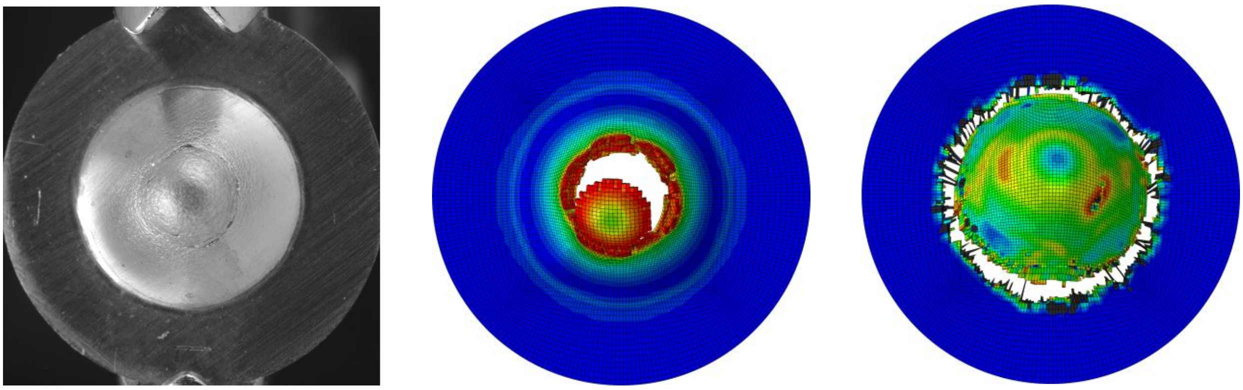

Fig. 4:Cracked small punch test specimen in a top view from the experiment (left) and numerical simulations depicting the damage predicted by Xue–Wierzbicki (center) and modified Bai–Wierzbicki (right) models.

5. Conclusions

The prediction ability of ductile fracture at a small punch testing of AISI 316L steel was presented using Xue–Wierzbicki and modified Bai–Wierzbicki models. Xue–Wierzbicki model predicted the crack initiation prematurely. It was due to the position of the initiation which was different from the one in the experiment. Bai–Wierzbicki predicted wrongly both the timing and the position of the ductile crack initiation.

Acknowledgement

This work is an output of project NETME CENTRE PLUS (LO1202) created with financial support from the Ministry of Education, Youth and Sports under the „National Sustainability Programme I".

References

Abbassi, F., Belhadj, T., Mistou, S. and Zghal, A. (2013) Parameter identification of a mechanical ductile damage using Artificial Neural Networks in sheet metal forming. Materials and Design, 45, 605-615.

Abendroth, M. and Kuna, M. (2003) Determination of deformation and failure properties of ductile materials by means of the small punch test and neural networks. Computational Materials Science, 28, pp. 633-644.

Kubík, P., Hůlka, J. and Petruška, J. (2011) Ductile fracture criteria in prediction of chevron cracks, in: Proc. Of Int. Conf. on Engineering mechanics 2011 (ed. Fuis, V.), Svratka, Czech Republic, pp. 339-342.

Kubík, P., Šebek, F., Hůlka, J. and Petruška, J. (2016) Calibration of ductile fracture criteria at negative stress triaxiality. International Journal of Mechanical Sciences, 108-109, pp. 90-103.

Kubík, P., Šebek, F., Petruška, J., Hůlka, J., Růžička, J., Španiel, M., Džugan, J. and Prantl, A. (2014) Calibration of selected ductile fracture criteria using two types of specimens. Key Engineering Materials, 592-593, pp. 258-261.

Manahan, M.P., Argon, A.S. and Harling, O.K. (1981) The development of a miniaturized disk bend test for the determination of postirradiation mechanical properties. Journal of Nuclear Materials, 104, pp. 1545-1550.

Peč, M., Kubík, P., Šebek, F., Návrat, T. and Petruška, J. (2016) Modeling of the blast load effects in explicit dynamics, in: Engineering mechanics 2016, Svratka, pp. 442-445.

Petruška, J., Návrat, T. and Šebek, F. (2012) A new model for fast analysis of leveling process. Advanced Materials Research, 586, pp. 389-393.

Petruška, J., Návrat, T., Šebek, F. and Benešovský, M. (2016) Optimal intermeshing of multi roller cross roll straightening machine, in: AIP Conference Proceedings, 1769, pp. 120002-1-4.

Rouse, J.P., Cortellino, F., Sun, W., Hyde, T.H. and Shingledecker, J. (2013) Small punch creep testing: review on modelling and data interpretation. Materials Science and Technology, 29, pp. 1328-1345.

Šebek, F., Kubík, P. and Petruška, J. (2014) Localization problem of coupled ductile failure models compared to uncoupled ones, in: Engineering mechanics 2014, Svratka, pp. 632-635.

Španiel, M., Prantl, A., Džugan, J., Růžička, J., Moravec, M. and Kuželka, J. (2014) Calibration of fracture locus in scope of uncoupled elastic–plastic-ductile fracture material models. Advances in Engineering Software, 72, pp. 95-108.

Wierzbicki, T., Bao, Y., Lee, Y.-W. and Bai, Y. (2005) Calibration and evaluation of seven fracture models. International Journal of Mechanical Sciences, 47, 4-5, pp. 719-743.