18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 461–468
Paper **#128**

SENSITIVITY ANALYSIS OF SMALL PUNCH TEST

J. Hůlka, P. Kubík, J. Petruška[1]

Abstract: *The paper deals with numerical simulation of penetration test called Small Punch Test (SPT). SPT is used to determine basic mechanical properties from a tiny piece of material. There are no generally accepted standards for this type of testing until now. The testing procedure drew a great interest in the last decade. "Code of Practice" was created based on the CEN Workshop 2007, which recommends both geometry, experiment performance and its evaluation. To obtain the mechanical properties from SPT is an indirect computational task. One of possible approaches to obtain yield strength and ultimate strength is the use of an inverse numerical simulation. There is a need to define the important variables, that will substantially influence the inverse simulation.*

Keywords: ***SPT, FEM, sensitivity analysis***

1. Introduction

Material properties of any component can change during their operation. The knowledge of the current values is desirable especially for extending service life of the component. To enable the evaluation of structural steels mechanical properties, penetration test of small bodies called the Small Punch Test is intensively developed. This non-standard type of test is preferred if there is shortage of material for samples. It is common for example in part of nuclear power plants, turbines, rotors, etc. The principle of SPT is punch penetration through the flat disc-shaped specimen. Schematic test arrangement is shown in Figure 1. The specimen is clamped between the upper and lower die and the punch penetrates the specimen up to failure. Punch displacement and reaction forces are recorded during the test. Punch can be either a ceramic ball or punch of steel with hemisphere ending.

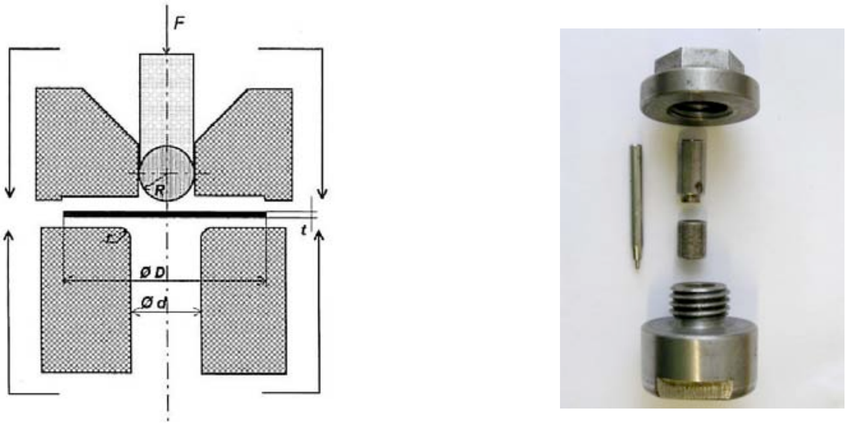


Fig. 1: Schematic representation of experimental assembly

Small Punch Test method originated in the early eighties of the last century in the U.S., where Manahan (1981) first published the method. Development of this method was under way parallel in Japan, too. The method focused on assessing the effect of irradiation on the material properties used in thermonuclear reactors. The biggest milestone in the development of this method was the establishment of document CWA 15627:2007 D/E/F on the basis of the CEN Workshop in 2007, which become the industry standard. This "Code of Practice" recommends not only the geometry of sample and tools, but also the testing course and its evaluation.

---

[1] Ing. Jiří Hůlka, Ing. Petr Kubík, Prof. Ing. Jindřich Petruška, CSc.: Institute of Solid Mechanics, Mechatronics and Biomechanics, Brno University of Technology; Technická 2896/2; 616 69 Brno; tel.: +420 777838541, e-mail: hulka@c-box.cz

For commercial use of this method, several technologies were developed cut the test specimen from the bulk of tested structures. They can be divided into two groups. The first is based on grinding off the sample and the second is based on electrosparking.

2. Numerical model variation

We are trying to simulate a real experiment with the help of finite element model (FEM). Our goal is to achieve computationally an identical force-deflection response, which is recorded from the experiment. The sensitivity analysis helps us to consider importance of variables that occur in the FE model. In this paper we analyse the influence of the following variables:

- FE mesh density
- modelling tools as rigid bodies
- influence of sample thickens
- influence of material model
- influence of friction between punch and sample
- influence of friction and forces among dies and sample

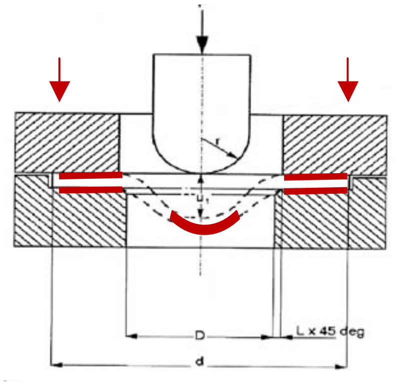


Fig. 2: Locations with friction influence

3. Material model

Very ductile austenitic steel ASTM A316L is investigated in our case. Specimens were made from rolled plate with a thickness of 20mm. We expected anisotropic mechanical properties because of rolling. To verify our assumption, the plate was cut in three directions, namely 0° in the longitudinal, diagonal 45° and 90° lateral direction. This is illustrated in Figure 3. Three specimens were made from prepared parts for uniaxial smooth tension test in every direction. Samples were made with longer clamping head, from which the SPT samples were made.

The average results of tensile tests in various directions of the plate are in Figure 4. It is possible to conclude from the results, that samples even at 45°do not show significant anisotropy. Material will be considered isotropic.

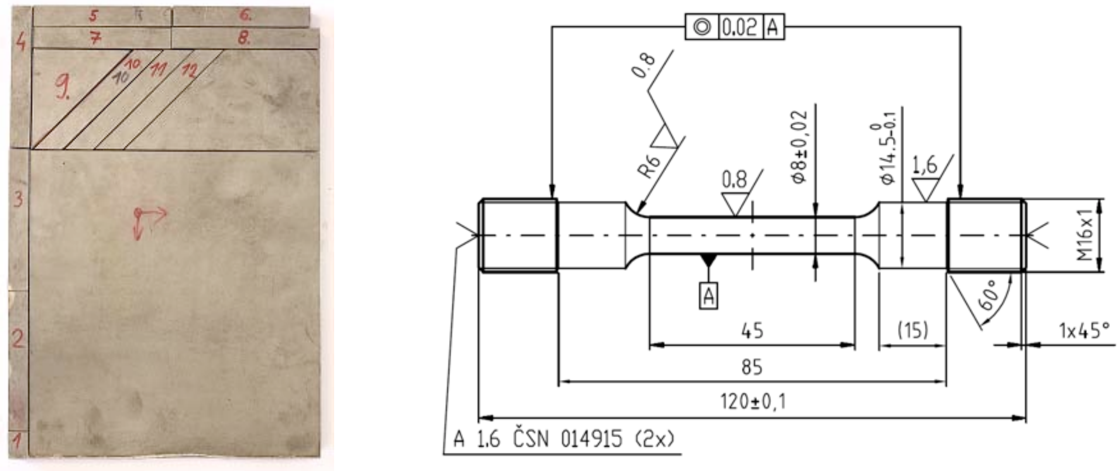


Fig. 3: Plate for the samples production (left), sample for uniaxial tension test (right)

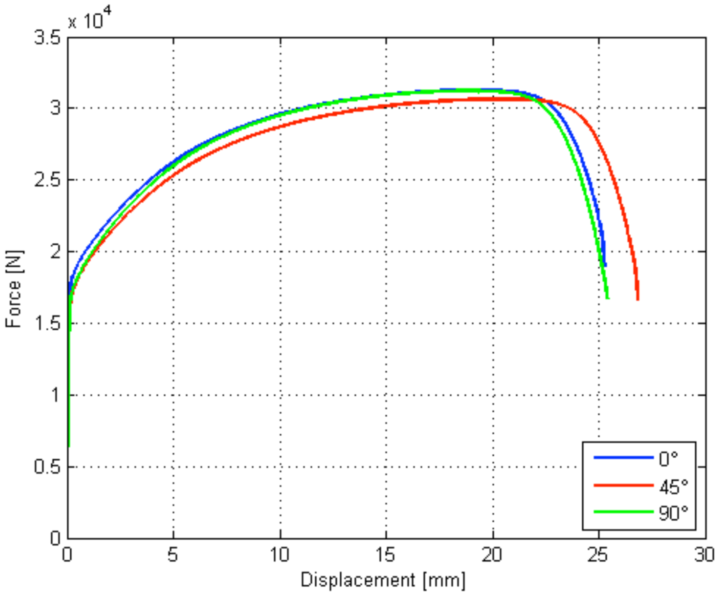


Fig. 4: Average values of tensile tests in three directions

The true stress-true strain curve is used as input data for elastic-plastic analysis. The uniaxial stress condition of circular smooth sample is valid only until ultimate strength. Strain value is commonly higher then break point, so it is necessary to calibrated the material model with help of parallel numerical simulation, as shown in Figure 5. There is used MLR correction recommended by Mirone (2006) or the initial estimate of the curve correction. Trial and error correction was used for greater accuracy. Figure 5 shows multilinear material model.

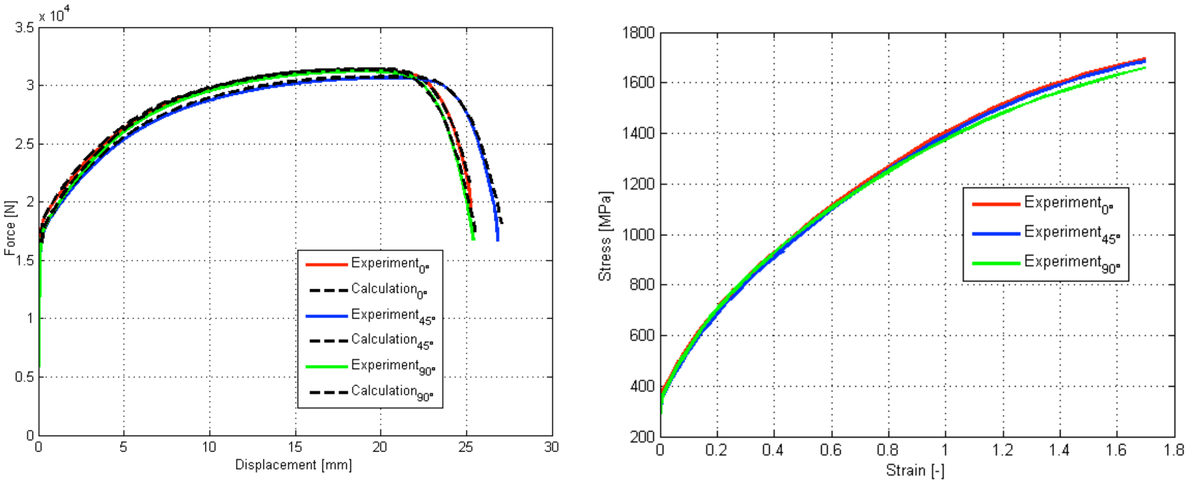


Fig. 5: Calibrated material model curves (left), the curves truth stress-strain (right)

4. SPT experiments

SPT samples were made from used tensile specimen's heads. In cooperation with Material & Metallurgical research Ltd. Ostrava, five penetration tests were performed in each of the direction. Experimental results are displayed in Figure 6. Considerable dispersion of measured values partly explains this sensitivity analysis. Fractures in the lower displacement are observed for some of the samples. Differences in fracture location are observed too. This issue will be investigated further.

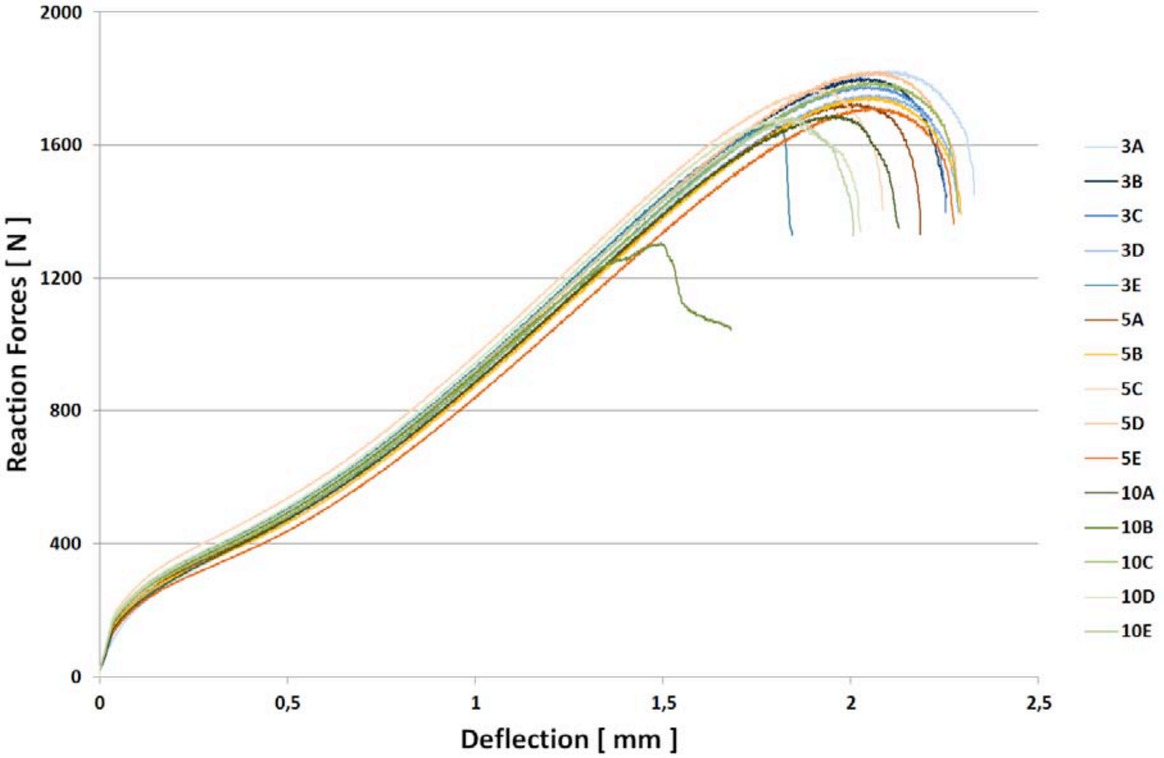


Fig. 6: SPT experiments

Tab. 1: Thickness of samples measured before the experiment

3=0°		10=45°		5=90°	
3A	0,505	***10A***	0,500	***5A***	0,490
3B	0,500	***10B***	0,495	***5B***	0,495
3C	0,505	***10C***	0,500	***5C***	0,505
3D	0,495	***10D***	0,505	***5D***	0,500
3E	0,505	***10E***	0,500	***5E***	0,485

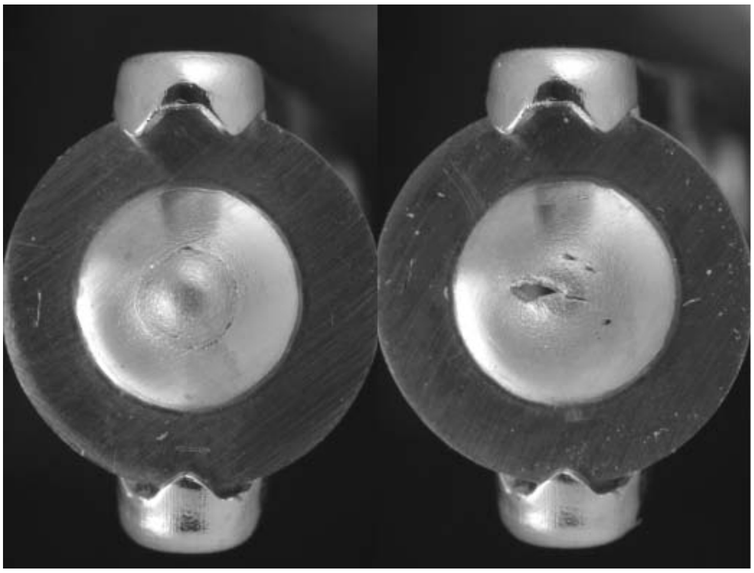
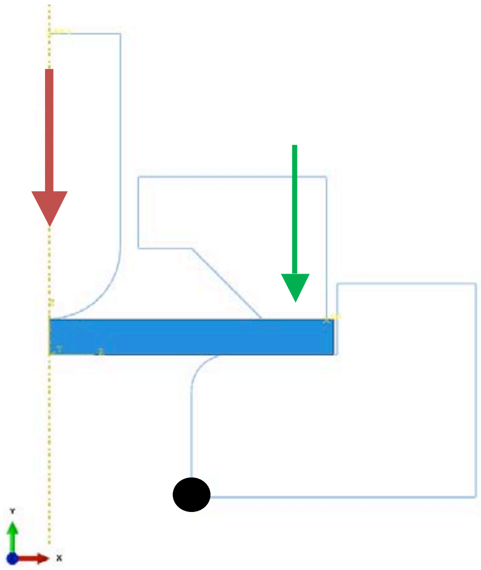


Fig. 7: SPT samples after the experiment with the standard (left) and unusual fracture (right)

5. Model of Small Punch Test

The computational model of SPT was created in explicit Abaqus code. Geometry of FE model is identical to the experiment assembly and recommended CWA 15627 except punch diameter, which is recommended 2,5mm. Geometry of FE model is in Figure 8.

Tools were modelled as "Rigid Body" and axisymmetrical FE model was used. Punch is moved in the y-axis direction. Contact force is prescribed to the upper die and the lower one is fixed.



Specimen diameter	8,0 mm
Specimen thickness	0,5 mm
Punch radius	1,0 mm
Inner diameter of lower die	4,0 mm
Lower die radius	0,5 mm

Fig. 8: Geometry of FE model with dimensions

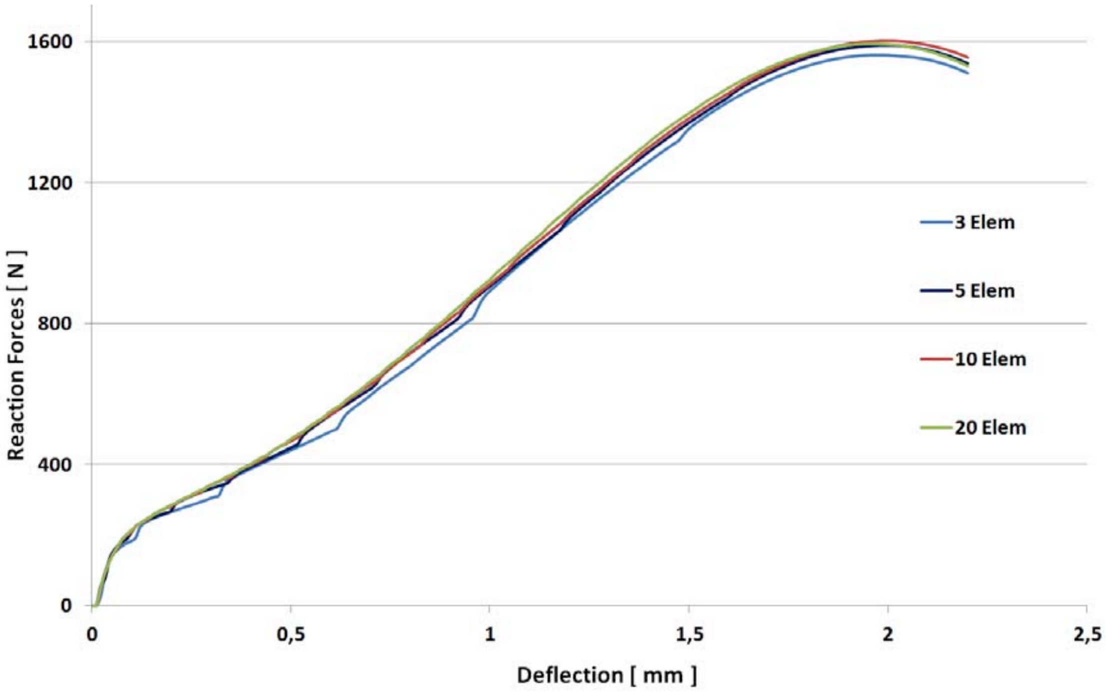


Fig. 9: Influence of FE density

6. Sensitivity analysis

Knowledge of variables based on sensitivity analysis is important for inverse problem. To minimize the scattering of measured values is necessary for quality output from the numerical simulation. We assume an ideal experimental tools shape in our case.

6.1 FE mesh density

Fixed upper and lower die represent the default state of the model. Coulomb friction model is used with the coefficient f=0,1. The same friction coefficient is used between the punch – sample and dies – samples. Material model is used for 90° (transversal direction).

The graph in Figure 9 shows that the model is adequately described with 5 - 10 elements in the through thickness direction of the sample.

6.2 Tools deformation

There is an effort to model tools as rigid bodies to shorten calculation time and to make the model more efficient. Displacement difference due to the punch deformation is shown in Figure 10. Displacements are measured between the ends of the punch. Tools were modelled as elastic bodies.

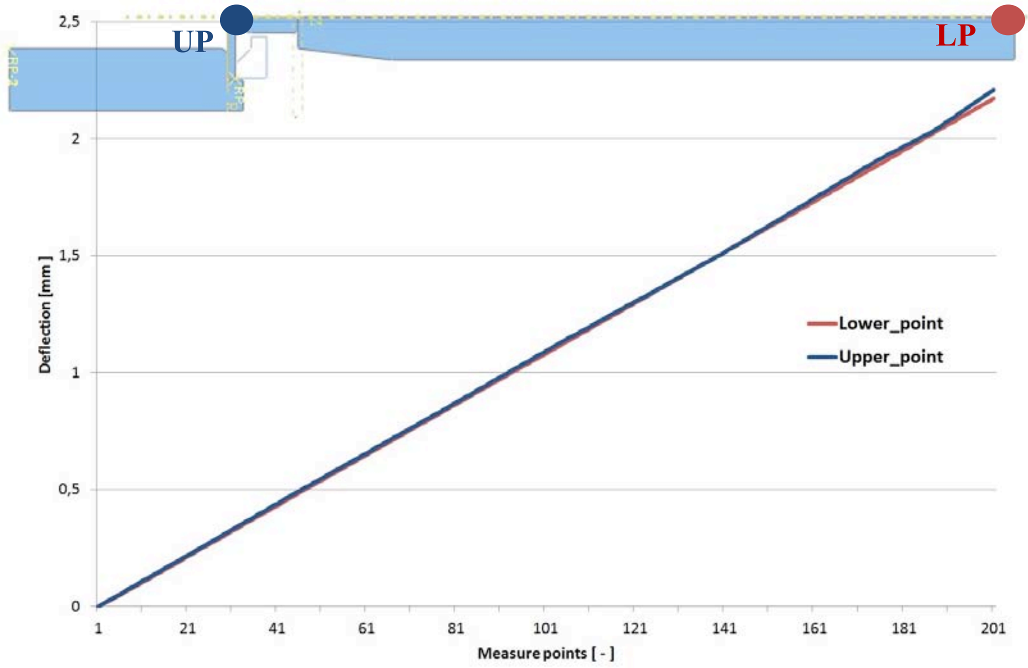


Fig. 10: Displacement differences on punch

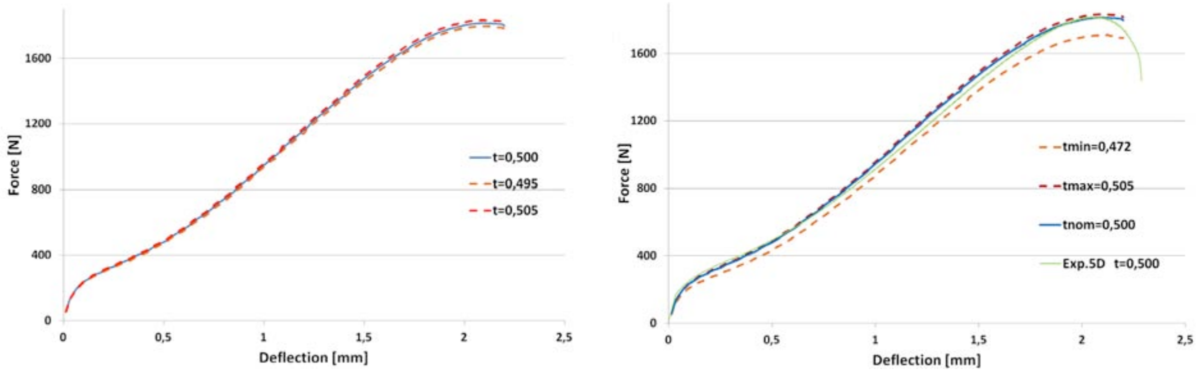


Fig. 11: Reaction forces according CWA thickness tolerances (left) and real values (right)

6.3 Influence of sample thickness

Samples production is not easy. Although there are mechanical productions of samples, most of them are produced by hand. Thickness and flatness of samples is prescribed by CWA. Table 1 shows the thickness-tolerance, which is recommended +-1% of the sample thickness (+-0,005mm). We assume ideal flatness of the sample in FE model and only the influence of thickness is studied. There is force dispersion according CWA tolerance on the left part of Figure 11. The right part of the figure shows force dispersion with real thicknesses used in the experiments.

6.4 Influence of friction between punch and sample

We distinguish between two places with friction in the model. One is the interface between the punch and the sample. The second is between the matrix and the sample, as shown in Figure 2. Friction coefficient is changed between the punch and the sample, see Figure 12. Coefficient of friction between the dies and sample was f=0,1.

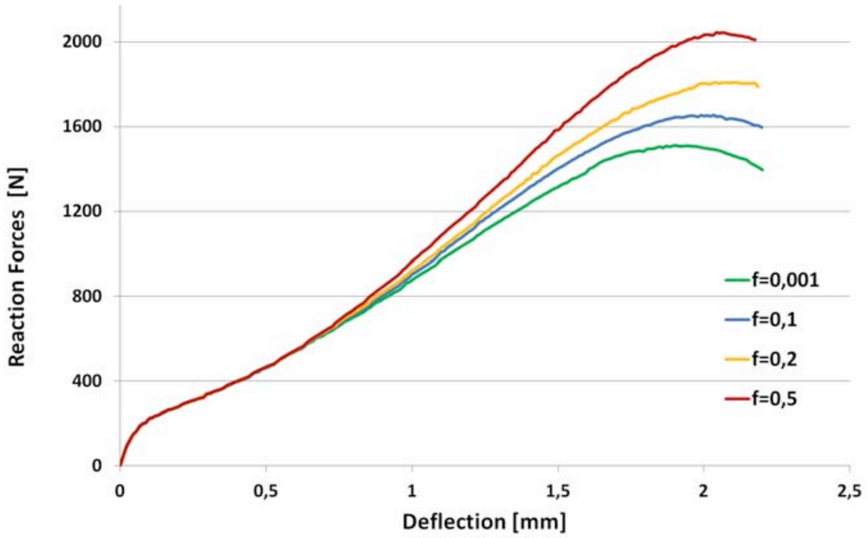


Fig. 12: Influence of friction coefficient variability between punch and sample

6.5 Influence of friction and upper die pressure variability

In Figure 13, we can see simulation results to quantify the effect of upper die pressure and friction variability on the test results.

6.6 Influence of material model calibration

It is always important to perform parallel numerical simulation by material model calibration. Differences in forces response using a model without material hardening after the yield stress, ultimate strength and material models calibrated at 0° and 90° direction are in Figure 14.

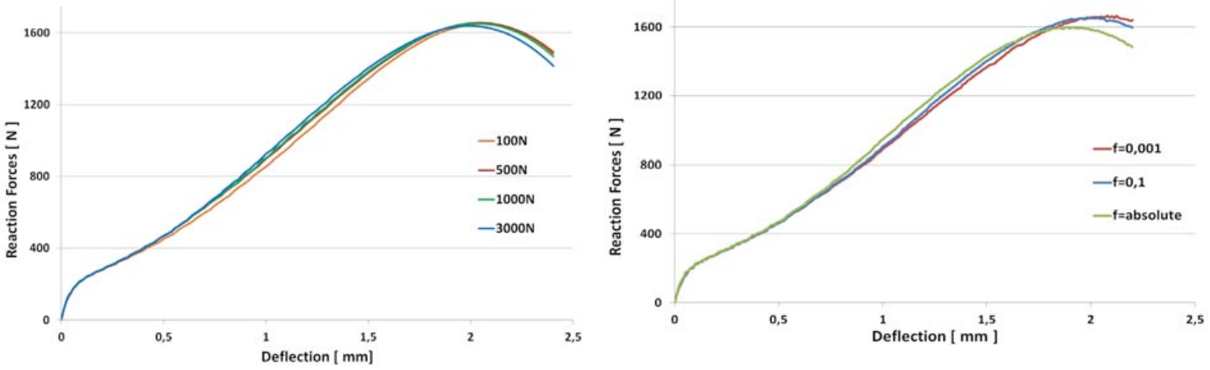


Fig. 13: Effect of die pressure (left) and friction coefficient value

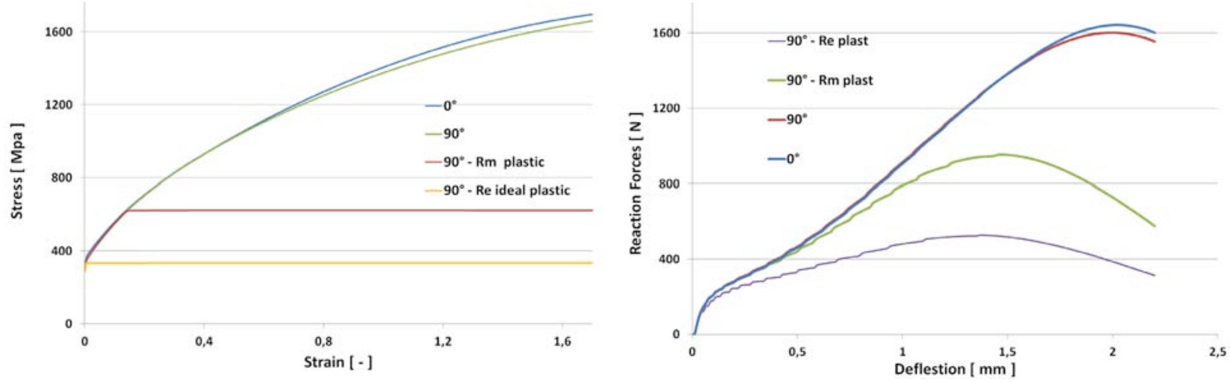


Fig. 14: Effect of material model to response forces

7. Conclusion

This paper presents a sensitivity analysis of SPT. Uniaxial tensile tests did not confirm the strong anisotropy of the material. SPT samples were prepared from heads of tensile specimens. Considerable dispersion of data was found from fifteen tests.

Sensitivity analysis was focused on the variables affects in the test. There are well calibrated material models, finite element density, value of the friction coefficient, the actual thickness of sample and tool deformation.

True stress – strain curve is the input to the elastic-plastic material model. The graph in Figure 14 shows that the maximum reaction force of SPT lies in the extrapolated part of curve which is obtained from uniaxial tensile test. This is reason to pay close attention to the calibration of the true stress-strain curve.

The value of Coulomb's friction coefficient plays a dominant role in the second part of test. At that time there is relative movement between the specimen and the punch. Static value of friction was used in chapter 6.4. Distribution of friction as static and dynamic one will be subject to further sensitivity analysis.

It is not easy to keep the prescribed thickness tolerance. This is due to small dimension of specimen and mostly handmade samples.

The influence of friction and pressure among dies and sample is not significant. Deformations of tools are not significant, too. Figure 9 shows, that a suitable mesh density of sample is 5-10 elements in thickness.

Acknowledgement

Financial help of the grant projects GA101/09/1630 and FSI-S-11-11/1190 is gratefully acknowledged.

References

CEN WORKSHOP AGREEMENT „Small Punch Test method for Metallic Materials“ (2007) CWA 15627:2007: D/E/F, Decenber 2007

Egan P., Whelan M.P., Lakestani F., Connelly M.J. (2007) Small punch test: An approach to solve the inverse problem by deformation shape and finite element optimization. *Comp. Mat. Science*.40, 33-39

Hurst R., Matocha K.(2010) The European Code of Practice for Small Punch Testing – where do we go from here? *Metallurgical Journal*, 63, 5-11.

Manahan M., Argon A., Harling O. (1981) The development of a miniaturized disk bend test for the determination of post-irradiation mechanical properties. *J. of Nuclear Mat.*, 103-104, 1545-1550.

Mirone G. (2006) Role of stress triaxiality in elastoplastic characterization and ductile failure prediction. *Eng. Fract. Mech.*, 74, 1203-1221