EFFECTS OF DEVICE IMPERFECTIONS ON SMALL PUNCH TEST

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Abstract

Description of the procedure and results are given for computer simulations of small punch test (SPT) performed on P92 structural steel. The maximum force calculated using the SPT simulation is about 5% higher than the measured value. The punch displacement at the maximum calculated force is 2% less than the measured punch displacement. Effects of several factors were analysed using the SPT simulation, such as friction between the test device and the test specimen, the geometry of the test device, and the clamping force. It was found that SPT results depend strongly on the amount of friction and on imperfections of the test device dimensions and geometry.

Keywords: Small punch test, imperfection, simulation, finite element method

1. INTRODUCTION

The finite element method is employed in engineering design on a routine basis for determining appropriate dimensions of structures and machines and for modelling metalworking processes. Commercially-available FE software tools enable engineers to solve static linear problems as well as the non-linear ones. Where a solution is sought for a stress-strain problem in the elastic range, modulus of elasticity (E) and Poisson's ratio (ν) are sufficient as input data for isotropic materials. In recent years, however, demand has grown for stress and strain calculations which allow for elastic-plastic behaviour as well [1], [2]. For accurate simulations of component behaviour involving isotropic plasticity, actual stress-strain data are required, i.e. models of the dependence of true stress on true strain. An accurate model of a ductile material can be constructed from an engineering stress-strain curve [3], [4], [5], [6] and [7].

When estimates of mechanical properties of in-service structures are needed, the small punch test (SPT) is often employed [8], [9] a [10]. As the name shows, SPT specimens are of small size. Thus, the subsequent disturbance to the structure from which they are taken is minimal and does not compromise its strength. In the light of this fact, SPT has been classified as one of non-destructive tests. Earlier studies used computer simulations of SPT to explore the effects of variation in the ball punch diameter, the test specimen thickness, the friction coefficient and the yield stress and work-hardening exponent of the specimen material. In these studies, an ideal geometric setup was employed and the test device was considered to consist of rigid bodies, [11] and [12].

The present contribution deals with simulation of small punch testing of P92 steel [13] and compares the effects of selected SPT parameters and test device imperfections on the test. These calculations comply with the requirements for the modelling of large deformation in test specimens. They also account for steel's plasticity characteristics (isotropic plasticity) and for friction on contact surfaces of the test device and the specimen.

2. SIMULATION OF SMALL PUNCH TEST

The geometry of the model represents a test device used by the company Výzkumný a zkušební ústav Plzeň with a disc-shaped test specimen with a diameter of 8 mm and 0.5 mm height [14]. The symmetry of the model with respect to the vertical axis of the test setup was exploited in its construction. Friction between the test device and the disc specimen is modelled using the f coefficient values between 0.07 and 0.2. The specimen is clamped in the device through forces C and D which are imposed by a swivel nut. A geometric model of the test device configured according to relevant drawings is shown in **Figure 1**. The materials of the test device (steels, INCONEL625, alumina) are modelled using their respective moduli of elasticity and Poisson's ratios.

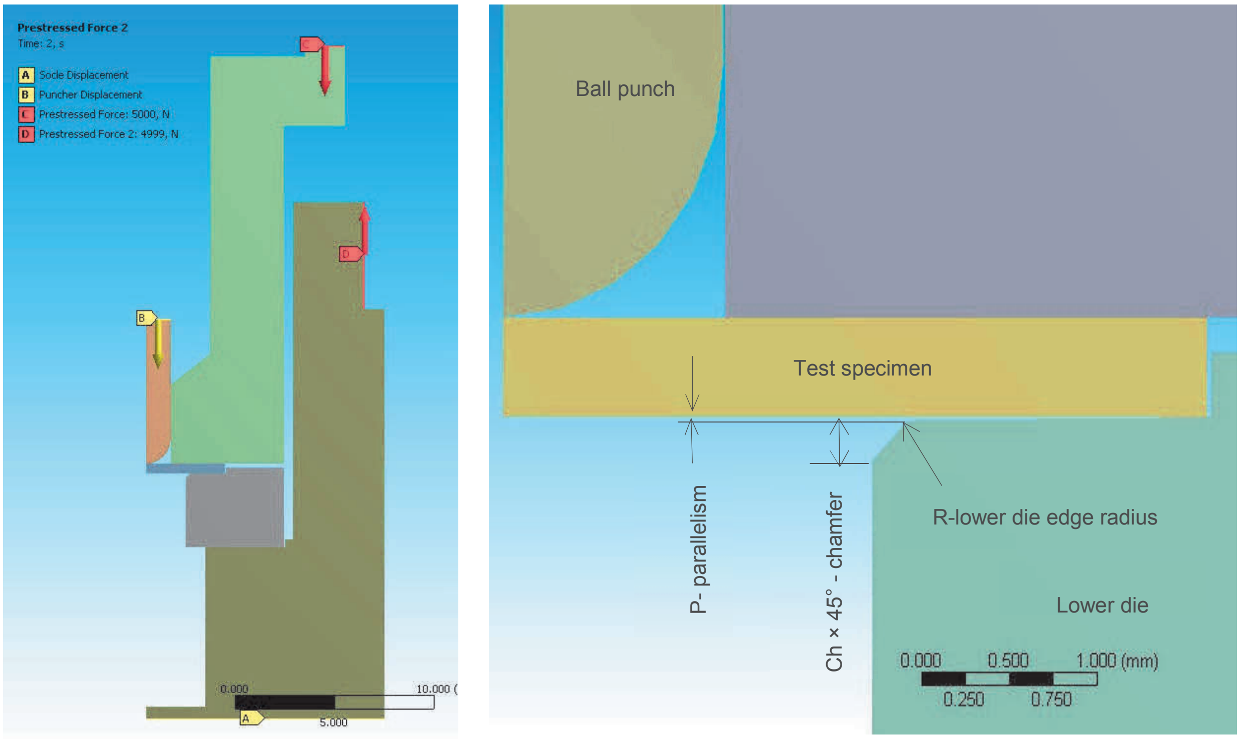

Figure 1 Geometry model and imperfections studied

Additionally, the material model of the lower die (INCONEL625) accounts for isotropic work hardening. In the drawing-based configuration, the friction coefficient is considered as f = 0.07 [15]. The geometric imperfections of the lower die explored in this study include an edge chamfer Ch = 0.3 mm (the chamfer specified on drawings is Ch = 0.2 mm), an edge radius R = 0.02 mm and parallelism error of the surface of the recess for accommodating the specimen P = 0.02 mm, as indicated in **Figure 1**.

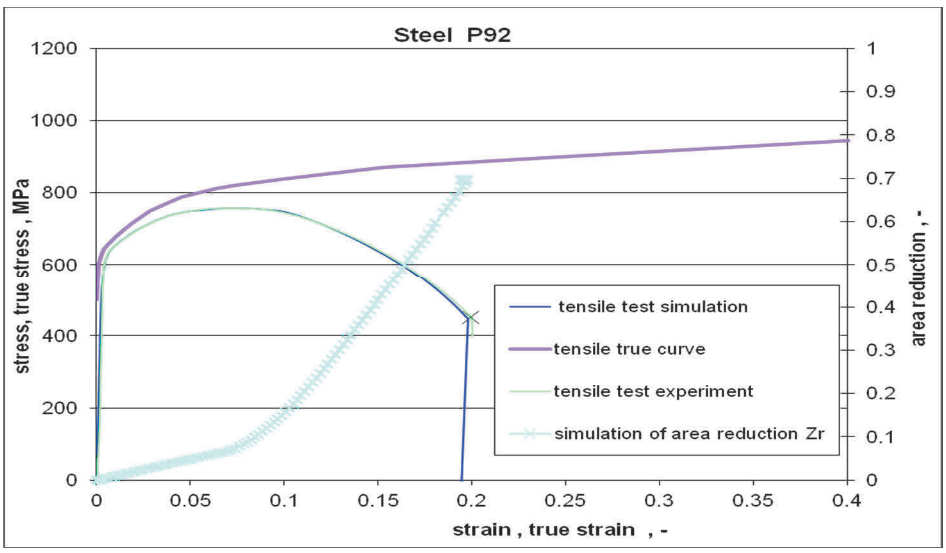

Figure 2 Tensile test plots for P92 steel

The input data for the P92 steel model included the modulus of elasticity E = 210,000 MPa, Poisson's ratio ν = 0.3 and a dependence of true stress on actual engineering plastic strain derived from a real-world tensile test data. The portion of this real-world stress-strain curve beyond the ultimate strength point had been corrected. The purpose of this correction was to ensure agreement between the real-world engineering stress-strain diagram and the one produced by simulation, as shown in **Figure 2**.

In the first step of the SPT simulation, a disc specimen is clamped in the test device and held by forces C and D. In the second step, the disc is held by forces and C and D and subjected to a load exerted by a moving punch until the prescribed punch displacement is achieved.

3. RESULTS AND EVALUATION OF SIMULATION

Total strain and HMH stress after the end of standard-configuration small punch test are shown in **Figures 3** and **4.**

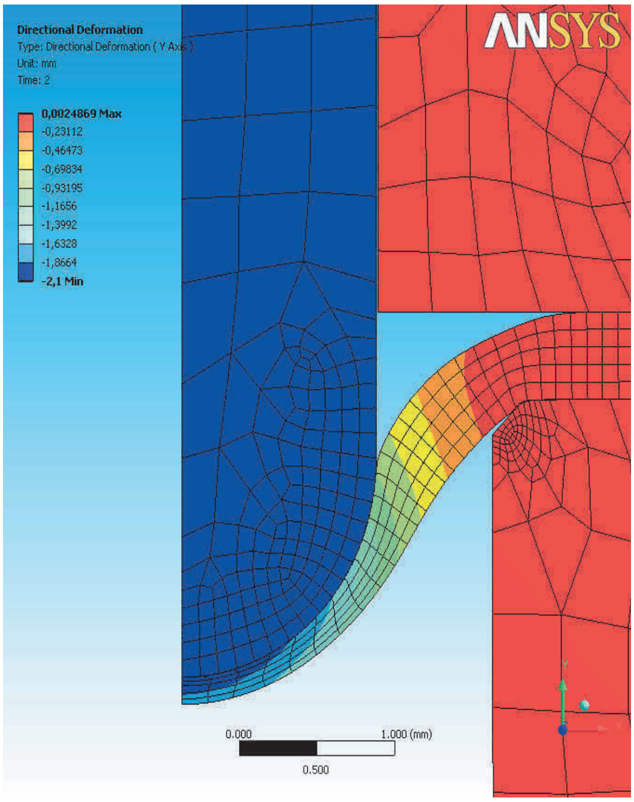

Figure 3 Deformation at the end of SPT

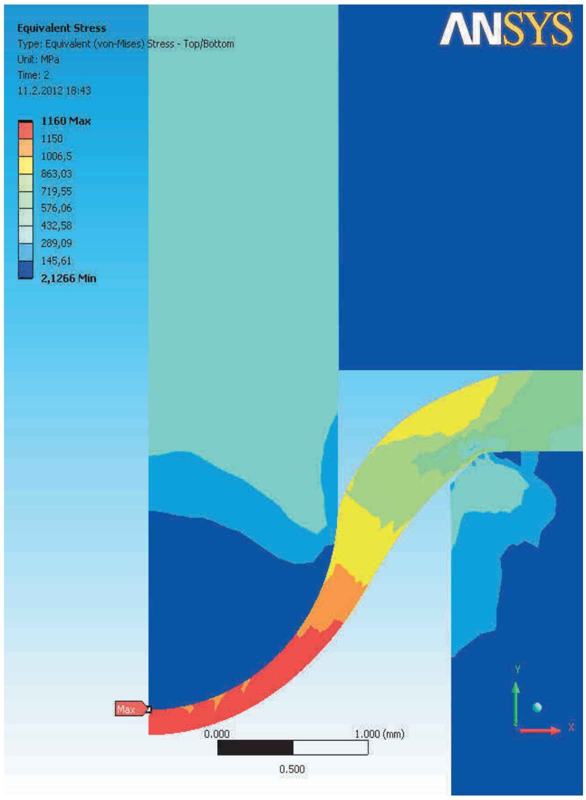

Figure 4 HMH stress at the end of SPT

The calculated dependences of the test force and the maximum HMH stress in the disc specimen on the punch displacement are plotted in **Figure 5**, as well as the curves from experiments reported in [16] (P92_molyko01 - 04). The calculated maximum test force is larger by 5% than the value measured in the real-world test. The calculated punch displacement at the calculated maximum force is lower by 2% than the measured value.

The simulated and real-world measured relationships between force and displacement differ significantly even at the start of the small punch test. It is clear from the HMH stress distribution in the disc specimen shown in **Figure 4** that the discrepancy occurs in the elastic range or in the early plastic range. As the extent and magnitude of plastic deformation increases, the discrepancy diminishes. This behaviour is in contradiction to the premise that simulation data should approximately match the real-world values in the early stages of the SPT and that they should only begin to deviate substantially after the onset of plastic deformation. After this finding, selected parameters which can affect the SPT results were re-examined: the clamping force magnitude, the imperfections of the test device and the friction between the test device and the specimen.

The effects of clamping force variation between 150 N and 5,000 N are illustrated in **Figure 6**. At low clamping force, the test force becomes a) lower between the start of the test and the displacement of approx. 1.3 mm and b) slightly higher beyond 1.5 mm displacement.

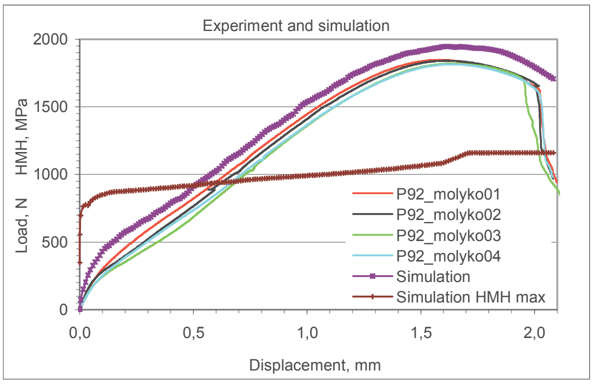

Figure 5 Force versus displacement - real-world experiment and simulation

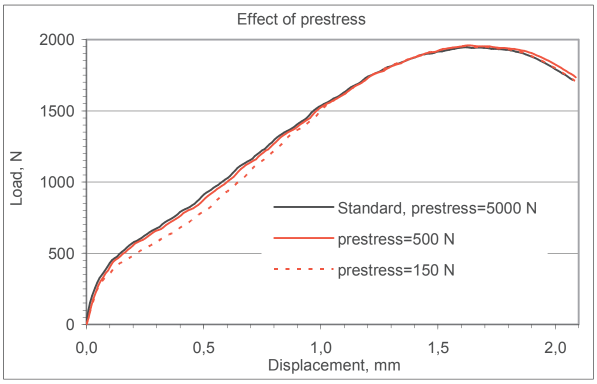

Figure 6 Effects of prestress

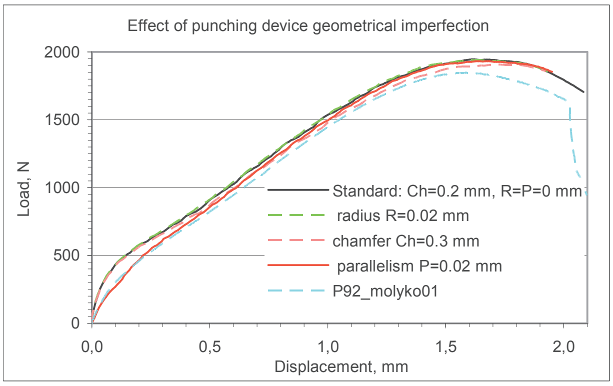

Figure 7 Effects of test device imperfections

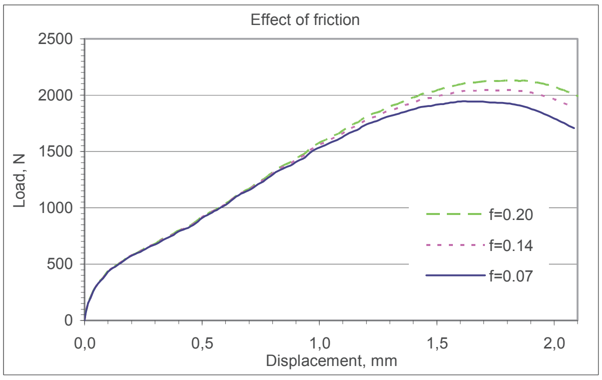

Figure 8 Effects of friction

Above 500 N, the effect of the prestress magnitude is negligible. There is a clear need to improve the reproducibility of SPT results by standardizing the disc specimen clamping procedure. The relationships between geometric imperfections of the lower die and SPT results are shown in **Figure 7** together with results of a real-world test. The lower die edge radius R = 0.02 was estimated on the basis of the permanent deformation of the edge after removal of the test force on the test specimen. This edge radius of the lower die has only a marginal impact on SPT results. By contrast, after the lower die edge chamfer increases to Ch = 0.3 mm and the parallelism imperfection of the lower die surface, which is in contact with the test specimen, increases to P = 0.02 mm, the dependence of force on displacement changes significantly. Once the edge chamfer is increased to 0.3 mm, the test force becomes reduced in the interval between the displacement of 0.25 mm and, in fact, the end of the test.

Parallelism error considerably reduces the test force, more so early in the test. As the punch displacement increases, this discrepancy diminishes. The discrepancy between the simulation results and the real-world SPT data may arise from the parallelism imperfection of the test device contact surfaces. In the light of the varying slopes of the real-world force-displacement plots seen in **Figure 5**, one may expect that imperfect parallelism between the disc specimen contact surfaces may have a significant impact on SPT results.

The effects of friction between the test device and the disc specimen is shown in **Figure 8**. Higher friction coefficient values lead to a significant increase in the test force beyond a displacement of approximately 0.75 mm. The amount of friction affects the location where the disc fails. At friction coefficient f = 0.07, the highest HMH stress, and thus the potential failure location, is found in the centre of the disc specimen, see **Figure 4**. At f = 0.2, the highest HMH stress occurs at approx. 0.6 mm radius where the disc becomes thinner, as seen in **Figure 9**. Simulations of the small punch test device imperfections hint at possible sources of discrepancies between simulations and actual test.

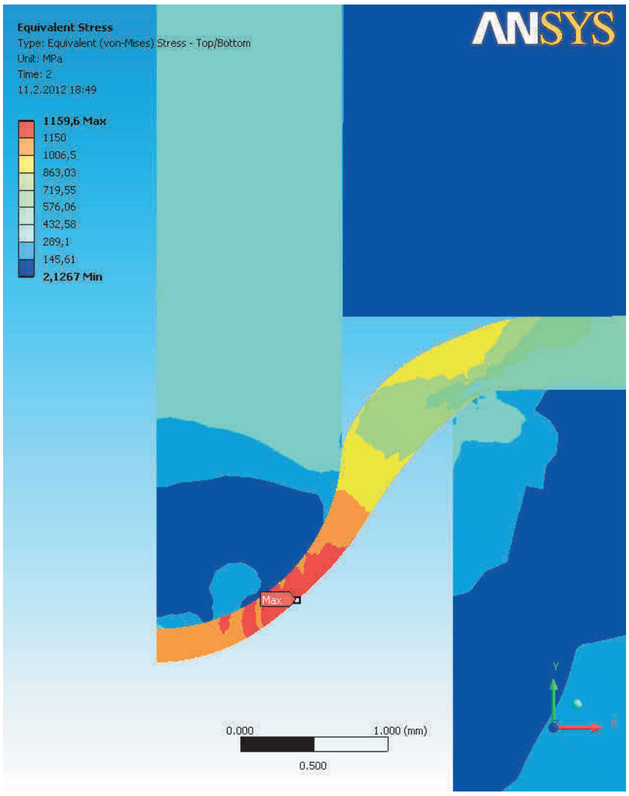

Figure 9 HMH stress at the end of SPT, f=0.2

Geometric imperfections of the test device and disc specimen and deviations from correct procedures have an unacceptable impact on the results of SPT. Since the main purpose of small punch testing is to collect data for predicting the behaviour and integrity of in-service structures, all available means should be exploited to ensure that correct and reproducible results are obtained from the test. Computer simulations of small punch tests appear to be an effective tool for studying the dependence of SPT results on materials properties and for developing more reliable test evaluation methods.

4. CONCLUSION

A real-world stress-strain diagram and the dependence of true stress on plastic deformation can be derived from a round bar tensile test data. The smallest data set which enables a real-world tensile test diagram for steel to be constructed comprises the stress and strain values at offset yield strength, at the ultimate strength point and at fracture. The results of simulated tensile and small punch tests are in good agreement with the results of their real-world counterparts. Where accurate estimates of true stress-strain parameters are demanded, it is recommended to modify the engineering stress-strain diagram based on tensile test simulations. The imperfections of the SPT device studied here shift the SPT curves towards lower test force values. The parallelism imperfection of the lower die causes the largest reduction in test force values at the start of the small punch test. Similar outcomes may be expected when the surfaces of test specimens suffer from parallelism errors of several hundredths of millimetre. Comparison between real-world tests and simulations of SPT hint at the effects of possible geometric deviations of the test device from drawings, the effects of random deviations of clamping force, and the test specimen geometric imperfections. Computer simulations of small punch testing appear to be an effective tool for identifying systematic and random errors of the test. They can also be used for exploring the cause-and-effect relationships between materials properties and results of SPT.

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