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# Small Punch Testing and Its Numerical Simulations under Constant Deflection Force Conditions

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*A comparison of results of small punch tests on miniaturized discs under a constant force with their simulation by means of FEM is presented. A heat resistant steel of type CSN 41 5313 (EN 10CrMo9-10) was selected for our investigations. The small punch tests as well as the necessary conventional creep tests on massive specimens were performed at 873 K. For simulations, the Norton power-law and the exponential relationships were applied in the FEM model of the SPT arrangement. Parameters of both relationships were derived from stress dependences of minimum creep rate obtained from the conventional creep tests. While at higher loads the Norton power-law yields results more comparable with those obtained from experiments, at lower loads the exponential relationship gives better results. The investigation also confirms the simple relation between stress in conventional tests and force in small punch tests resulting in identical time to fracture of both types of tests.*

***Keywords***: small punch test, finite element method, parametric study, creep, fracture mechanics.

**Introduction**. Small punch tests (SPT) on thin disk specimens can be considered as one of the promising methods for the determination of the residual – or at least guaranteed – life of exposed parts of power generation and thermal facilities. Due to small specimen dimensions it may be classified as a non-destructive method in this industrial sector. Recently, there have been significant efforts by European and US research groups to standardize the dimensions and test conditions of SPT at low, ambient, and high temperatures [1]. Currently, a good progress has been achieved in the numerical modeling of the SPT at room and low temperatures, for the SPT at constant deflection rate conditions [2, 3]. Preliminary results at IPM demonstrated that SPT-CDF (at constant deflection force conditions) represent an apt tool for obtaining local creep properties at operational temperatures. It was shown that the results of these tests can be correlated with the results of conventional tests on massive specimens [4, 5]. Thus, the small punch technique should provide important information for safety procedures. However, the currently applied relations between results of conventional testing and small punch tests are purely empirical. The aim of this work was to apply the finite element method (FEM) for the verification and better understanding of the small punch test application in the assessment of the creep resistance and either the residual or guaranteed life time for heat resistant steels.

**Procedures**. The material chosen for this study was a low alloy heat resistant steel CSN 415313 (EN equivalent 10CrMo9-10), which is widely used in the Czech power generation industry. The testing temperature was set to be 600°C (873 K), which is the maximum recommended operation temperature for this steel in long-term service. In order to obtain accurate relationships between the results of conventional and small punch tests, the comparison of their results obtained on the same heat of steel with identical heat treatment as well as mechanical treatment was necessary. Therefore, both types of tests were performed under conditions leading to comparable values of time to rupture (up to 1000 hr). Stress (load) ranges were 80 to 200 MPa for conventional creep tests and 200 to 500 N for SPT. Several conventional tensile tests at the testing temperature were also performed in order to determine the static material properties, namely the Young modulus.

**Results and Discussion**. A comparison of the experimental values of the force $F$ and the stress $\sigma$ resulting in identical time to fracture in both types, i.e., SPT, and conventional creep tests (see Fig. 1) confirmed the simple relation between the force and stress in the form [4, 5]:

$$F = \Psi\sigma, \tag{1}$$

where the factor $\Psi$ reaches values close to 2.6 for some heat-resistant steels. The value $\Psi \cong 2.5$ was obtained from the present experiments. The plot of experimental and numerical results shown in Fig. 2 will be discussed further.

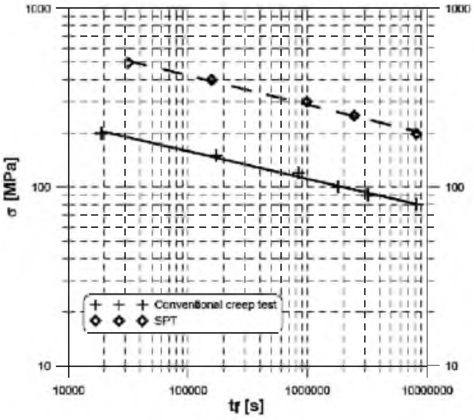

Fig. 1

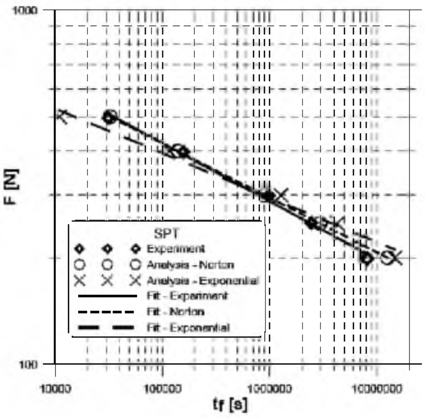

Fig. 2

Fig. 1. Comparison of the load and stress at identical time to fracture for conventional creep tests and SPT.

Fig. 2. Comparison of the load vs. time to fracture for experimental and calculated SPT data.

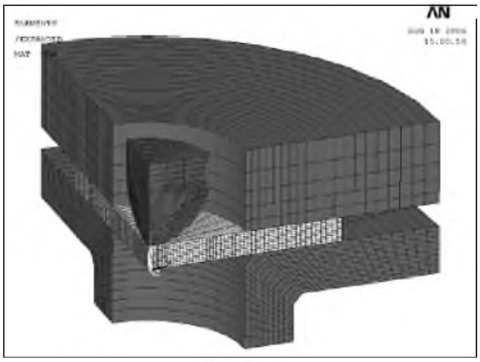

Fig. 3

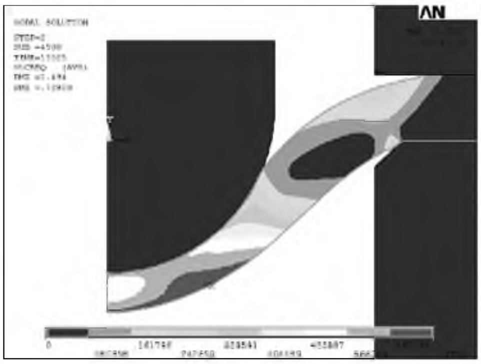

Fig. 4

Fig. 3. A 2D axisymmetric FE model of the SPT arrangement, expanded to 3D.

Fig. 4. Equivalent creep strain plot for a specimen loaded with $F = 500$ N at $t = 13{,}525$ s.

A two-dimensional axisymmetric model of the SPT arrangement was formulated in the ANSYS FEM system [6]. The model is shown in Figs. 3 and 4. The contact between the specimen and arrangement was modeled using surface to surface contact elements with the friction coefficient $f = 0.1$. The parametric study of various friction conditions for SPT under constant deflection rate was done in [7]. Application of two types of constitutive creep models in the numerical analysis was performed using the Norton power-law (Eq. (2)) and the exponential relationship (Eq. (3)):

$$\dot{\varepsilon}_{cr} = B\sigma^{n} \tag{2}$$

and

$$\dot{\varepsilon}_{cr} = Ce^{\sigma/m}. \tag{3}$$

Both of these equations are applicable mostly to the secondary creep rates. From the regression analysis of the conventional creep test data we obtained the coefficients $B = 3.257\cdot10^{-21}$, $n = 6.505$ for the Norton power-law and $C = 2.68\cdot10^{-10}$, $m = 21.4$ for the exponential form.

The load cases were numerically solved for the identical number of load levels as the performed SP testing. The experimental SPT curves at two different load levels and the relevant calculated curves are compared in Figs. 5 and 6. The experimental SPT curves for the repeated tests at a load level of 500 N are shown in Fig. 7, they demonstrate an acceptably small scatter.

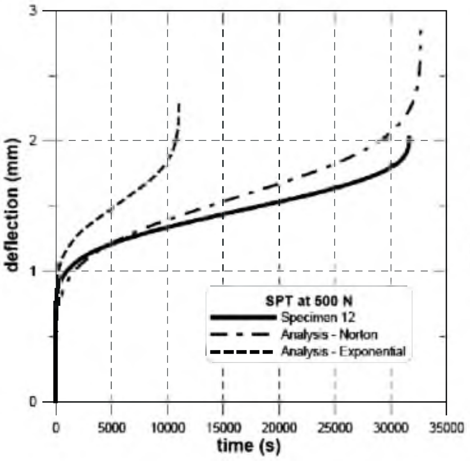

Fig. 5

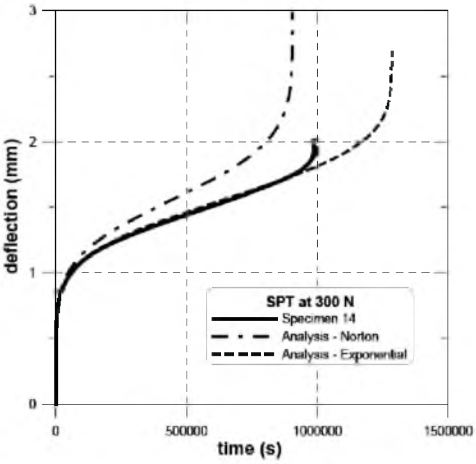

Fig. 6

Fig. 5. Experimental and calculated SPT curves at $F = 500$ N.
Fig. 6. Experimental and calculated SPT curves at $F = 300$ N.

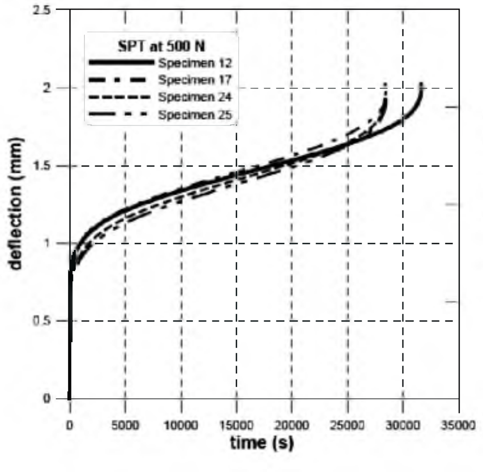

Fig. 7

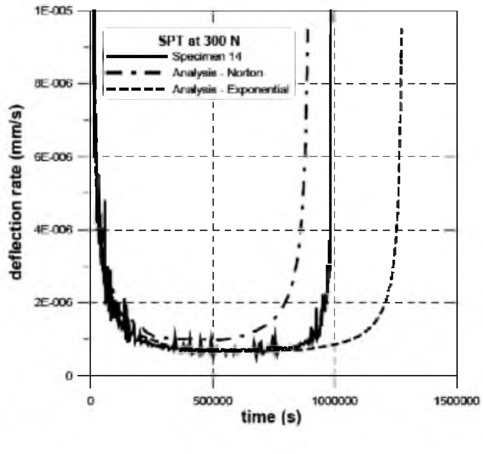

Fig. 8

Fig. 7. Experimental SPT curves at $F = 500$ N, illustration of test reproducibility.
Fig. 8. Experimental and calculated SPT deflection rate curves at $F = 300$ N.

A very good correlation of time to fracture was obtained for the Norton constitutive model, the exponential model gives too conservative results for high load levels and non-conservative ones for lower load levels (see Fig. 2). In spite of this, for lower load conditions the exponential model provides a better fit of the analysis results with the experiment at the primary and secondary creep stages (as shown in Fig. 6). A comparison of creep deflection rates for load $F = 300$ N between the test and numerical analysis results is shown in Fig. 8.

The FE model does not include any damage modeling. Therefore, the tertiary part of the calculated creep diagram is driven mainly by the geometrical softening (a local decrease in the specimen thickness). This leads to a slightly different shape of the tertiary region of the creep curve as compared to the test data. However, it does not seem to influence substantially the calculated life-time to be much different from the life-time measured on the specimen. Implementation of the damage modeling, for example with the use of a so-called element death technique or application of creep constitutive models that account for damage, could further improve the capabilities of the SPT FE model in order to describe more realistically the tertiary creep stages.

**Conclusions**. The SPT under constant deflection force can be well simulated by means of the finite element method and relatively simple creep constitutive models such as the Norton power-law or the exponential relationship. The adequacy of the calculated results can be further improved either by including the damage modeling in the SPT model or using more complex constitutive models that can well describe all three creep stages of the material behavior.

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