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Study of the upper die clamping conditions in the small punch test

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ABSTRACT

A parametric study of small punch tests on miniaturized discs under constant deflection rate and constant force has been performed to study the influence of various upper die conditions on the test results. A comparison between the experimental results and the simulations by means of the finite element method is presented, under different clamping conditions. Heat resistant steel P22 has been selected for this investigation. The elasto-plastic behaviour of the disc was described by multilinear isotropic hardening. Norton power-law and exponential creep constitutive relationships have been applied in the ANSYS FE model of the SPT arrangement under creep conditions. The investigation confirms relatively small influence of the upper die conditions for both types of small punch tests for the steel under investigation.

1. Introduction

Small punch tests on thin disc specimens (SPT) can be considered as one of the promising methods for the determination of the residual life of exposed parts of power stations and industrial plants under high-temperature operating conditions. Due to the small specimen dimensions, it may be classified as a non-destructive method in this industrial sector. Recently, in order to improve its applicability, there is ongoing significant effort worldwide to standardize the dimensions and test conditions of SPT at low, ambient and high temperatures [1]. Currently, there is good progress in the numerical modeling of the SPT at room and low temperatures for the SPT-CDR (at constant deflection rate conditions) [2,3]. Other results have demonstrated that SPT-CF (at constant force conditions) represents an appropriate tool for obtaining local creep properties at operational temperatures. It has been shown that the results of these tests can be correlated with the results of conventional tests on conventional specimens [4–6] and numerical modeling can give useful information about the disc time-dependent deformation behaviour [7,8]. However, there are still some doubts about the sensitivity of the SPT results to boundary conditions. Among the usually considered as critical boundary conditions, there is one of outstanding significance, which is the torque or the force applied to clamp the specimen between the upper and lower die. It is of extreme importance, since there are some authors [9,10] who do not use the upper die, especially for testing brittle materials, while some others strongly recommend its utilization.

The aim of this work is to study various upper die conditions and their influence on the test curves (CDR and CF). In order to achieve this goal, experimental and numerical analyses have been performed under different clamping conditions. By means of parametric finite element models of the SPT setup, which had been previously calibrated with experimental results, it has been possible to verify and to give a better understanding of the particular influences of the different upper die conditions.

2. Materials and procedures

2.1. Material

The material chosen for this study was a low alloy heat resistant steel CSN 415313 (P22 or EN equivalent 10CrMo9-10), which is widely used in the Czech power generation industry. Its mechanical properties were determined by means of 6 tensile tests at room temperature and 3 at 600 °C, which is the maximum recommended operation temperature for this steel grade in long-term service conditions. The material tensile properties are shown in Table 1. In addition, its Ramberg-Osgood parameters were also evaluated according to Eq. (1), as it can be seen in Table 2.

$$\varepsilon = \sigma/E + K(\sigma/E)^n \quad (1)$$

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Table 1
Tensile properties obtained from the uniaxial tests.

Temperature (°C)	Young modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)
20	206.0	430.0	687.9
600	157.2	331.8	460.4

Table 2
Ramberg-Osgood parameters obtained from tensile tests.

Temperature (°C)	*K*	*n*
20	9.65E+10	5.95
600	1.44E+27	12.19

In Eq. (1), ε is the total strain, σ is the applied stress (MPa), E is the Young modulus (MPa) and K and n are the Ramberg-Osgood parameters.

The material creep properties in high temperature conditions have also been obtained at the same temperature (600 °C). A total of 7 creep tests have been performed, at stress ranges in between 80 and 250 MPa and times to rupture up to 1000 h. Results were used to obtain the Norton and exponential creep parameters according to Eqs. (2) and (3).

$$\dot{\varepsilon}_{cr} = B\sigma^{n} \quad (2)$$

$$\dot{\varepsilon}_{cr} = Ce^{\sigma/m} \quad (3)$$

In Eqs. (2) and (3), $\dot{\varepsilon}_{cr}$ is the material creep strain rate (1/s) and B, C, n and m are material parameters. Both these equations are mostly applicable for secondary creep rates. The coefficients have been obtained from the regression analysis of the conventional creep test data, being $B = 3.257 \times 10^{-21}$, $n = 6.505$ for the Norton power-law and $C = 2.68 \times 10^{-10}$, $m = 21.4$ for the exponential form.

2.2. Small punch tests

SPT-CDR were performed at room temperature and SPT-CF were performed at 600 °C, at load ranges between 200 and 500 N, in order to reach comparable times to rupture with the conventional tests. Two different clamping conditions were tested for both SPT-CDR and SPT-CF: without upper die (the specimen is able to lift up around its perimeter during the test) and with upper die.

In order to perform the tests according to CEN [1], a constant-load cantilever creep machine was adapted for small punch testing and equipped with a stepping motor. During the test, a precision manufactured ceramic ball made of FRIALIT® F99.7 is pushed against the specimen, which is supported by a receiving die with a diameter of 4 mm. The diameter of the ball is 2.5 mm. The loading side of the cantilever is forced to move down by a constant rate, which corresponds to the deflection rate at the specimen centre of 0.005 mm/s (0.3 mm/min). The force acting on the specimen is measured using the load cell and the central deflection is measured using the LVDT extensometer. Tests at elevated temperatures are performed in a protective atmosphere of purified argon. In this case, temperature is measured by a thermocouple placed in the receiving die hole close to the specimen. The technique is described in more detail elsewhere [4].

Regarding the specimens dimensions, $h_0 = 0.500 \pm 0.005$ mm thick samples were employed, with ∅8 mm, according to CEN [1]. To achieve such dimensions, small pieces were cut by means of electro-discharge machining (EDM). Afterwards, the specimens were ground under water on metallographic papers (grit 200–2500) until achieving the desired thickness, without modifying their microstructure, according to CEN [1].

The results obtained have been employed to evaluate the material properties. Regarding the SPT-CDR, several approaches have been proposed during the last decades to obtain the tensile properties. In this paper, three different proposals have been selected according to their significance, which can be seen in Table 3.

In the equations shown in Table 3, s_y is the yield strength (MPa), $F_{I\text{–}II}$ is the load corresponding to the first inflection point in the load-deflection curve (LDC) (N), t_0 is the initial thickness of the sample (mm), $F_{y(h/10)}$ is the crossing point between the LDC and a straight line parallel to the initial slope of the curve with an offset deflection of $h_0/10$ (N), $F_{y(CEN)}$ is the vertical projection of the crossing point of the two tangents on the test curve as recommended by [1], s_u is the ultimate strength (MPa), $F_{II\text{–}III}$ is the load corresponding to the second inflection point (N), F_m is the maximum load (N) and d_m is the deflection corresponding to the maximum load (mm). The previous parameters are described in more detail elsewhere [11,12].

Regarding creep analysis, in order to obtain accurate relationships between the results of conventional and small punch tests, the comparison of results obtained at the same temperature and same time to rupture has been performed, according to Eq. (4) [1].

$$F/\sigma = 3.33k_{SP}R^{-0.2}r^{1.2}h_0 \quad (4)$$

In Eq. (4), F is the applied force in the SPT_CF (N), k_{SP} is the SPT creep correlation factor, R is the radius of the receiving aperture (2 mm) and r is the radius of the punch indenter (1.25 mm).

2.3. FE modeling

A numerical model of the SPT was built in the finite element system ANSYS with use of the axisymmetric elements PLANE182. For modeling the contact surfaces, elements CONTA171 and TARGE169 have been used. The FE model is shown in Fig. 1. The geometrical and material characteristics can be input as parameters. The applied material properties have been derived from conventional testing and the aforementioned dimensions have been employed. Regarding the friction coefficients, a value of 0.2 has been applied for the SPT-CDR and between 0 and 0.5 for the SPT-CF and no damage model has been introduced in the FE model.

In the FE model, the load is applied as a vertical displacement of the punch in SPT-CDR experiments and as a constant load applied on the punch in SPT-CF experiments. The boundary condition on the lower die edge is $u_y = 0$.

In order to analyse different clamping scenarios, several variants of upper die boundary conditions have been evaluated:

(a) Vertical displacement $u_y = -0.05$ µm of the upper die edge. According to the FEM, it results in a 700 N vertical force at room temperature and in 380 N at 600 °C. It should simulate a torque fixing the upper die.
(b) Vertical displacement $u_y = 0$ of the upper die edge. It results in a 0 mm gap between the upper die and the specimen, without the application of any force.

Table 3
Different approaches employed to obtain the material tensile properties by using SPT-CDR results.

Yield strength (MPa)	Ultimate strength (MPa)	Authors
$s_y = 1.35\frac{F_{I\text{–}II}}{h_0^2}$	$s_u = 0.74F_{II\text{–}III} + 0.17F_m$	Lacalle [11]
$s_y = 0.35\frac{F_{y(h/10)}}{h_0^2}$	$s_u = 0.28\frac{F_m}{d_m h_0}$	García [12]
$s_y = 0.55\frac{F_{y(CEN)}}{h_0^2} - 59.863$	$s_u = 0.52\frac{F_m}{d_m h_0} - 170.57$	Hurst and Matocha [13]