TWO-PARAMETER CHARACTERIZATION OF NOTCHED SPECIMEN UNDER CREEP

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The creep fracture behaviour of a notched specimen was studied for materials with prevailing Norton-type creep. New global parameters defining properties of stress and strain field in the whole notch region are introduced and calculated. It is concluded that there are two parameters controlling the lifetime of notched specimens: the first one is connected with the lifetime of smooth specimens and corresponds to applied load level, the second one expresses the influence of the size and geometry of the notch. The results of numerical simulations are compared with experimental findings for P91 steel.

Key words: fracture, creep, stress triaxiality, creep strain rate, finite element method, P91 steel, two-parameter description

DVOUPARAMETROVÝ POPIS VZORKŮ S VRUBY PŘI CREEPU

Je studováno lomové chování vzorků s vruby při creepu pro materiály s převládající oblastí stacionárního tečení popsané Nortonovým vztahem. Jsou navrženy a vypočteny globální parametry určující vlastnosti napěťového a deformačního pole v okolí vrubů. Je ukázáno, že existují dva parametry, které definují životnost vzorku s vrubem při creepu: první souvisí s životností hladkého vzorku a odpovídá velikosti aplikovaného napětí a druhý popisuje vliv velikosti a geometrie vrubu. Navržený postup umožňuje odhadnout životnost vzorku s vrubem na základě měření provedených na hladkém vzorku a výpočtů uvažujících tvar a velikost vrubu. Numerické výsledky jsou srovnány s experimentálními daty pro ocel P91.

1. Introduction

Notches occur very frequently in structural components due to the particular working conditions. Generally, notches produce concentrations of stress and they

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cause the stress state to change from uniaxial to multiaxial throughout the specimen. Moreover, under creep, the stress fields redistribute with time; the high axial stress components that exist in the notch root decrease with time. All these factors influence the lifetime of the notched body [1]. A comparison of the fracture behavior of smooth sided and notched specimens at the same net section stress shows that a notch can affect the lifetime of a body either positively (notch strengthening) or negatively (notch softening) depending on the nature of the material, the geometry of notches and the loading conditions (temperature, level of applied load, etc.), see e.g. [2, 3].

An understanding of the effects of such notches is essential in preventing the failure of components, and in analyzing failures when they have occurred, the fracture behavior of notches under creep has been studied in many papers. The available data show that the most decisive factor for the notch behaviour is the degree of the stress triaxiality due to the presence of the notch. The axial plastic deformation is constrained in the triaxial stress state field [4–7]. This is the reason why the lifetime in the case of the high-triaxiality circumferential notches (i.e. cylindrical bars) is higher than the lifetime in the case of low-triaxiality through-thickness notches (i.e. plates) under the same net section stress and comparable stress concentration factor [6, 7]. Several procedures for the quantitative evaluation of the notch-strengthening effect have been proposed. They are based either on different types of equivalent stresses [4, 5, 6, 8–10] or on continuum damage mechanics [11–14]. None of these procedures seems to cover all the cases and none of them seems to be accepted generally.

In this paper the creep fracture behavior of a notched specimen is numerically simulated for materials with prevailing Norton-type creep. The objective of the paper is to quantify the effects of the size and geometry of a notch on the time to rupture under creep for P91 steel. To this end

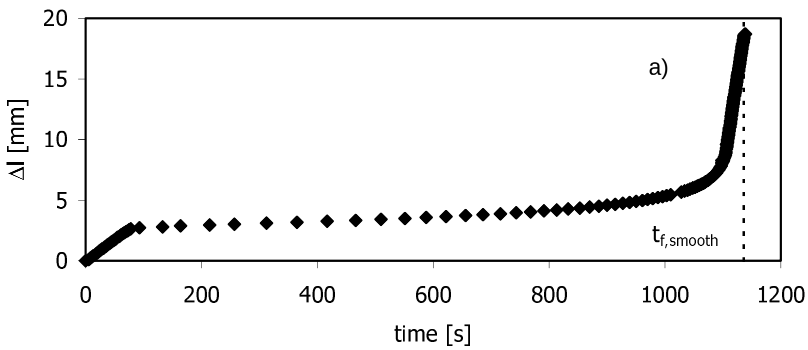
(1) numerical simulations were performed to study the effects of the size and geometry of a notch on the stress and strain distribution in the whole specimen,

(2) the influence of the multiaxial stress state generated by the existence of a notch was expressed by variables of local and global character,

(3) the fracture behaviour of smooth-sided and notched specimens at the same net section stress was compared and a correlation between time to fracture and global characteristics were found.

2. Experimental findings

The material data used in the present study were measured on cylindrical specimens of an advanced 9 % Cr steel of type P91 (see [15] for chemical composition) at a temperature of 600 ℃. These data were used as the input data for numerical simulations. The elongation was continuously measured by linear variable differential transformers coupled with a digital data acquisition system. All



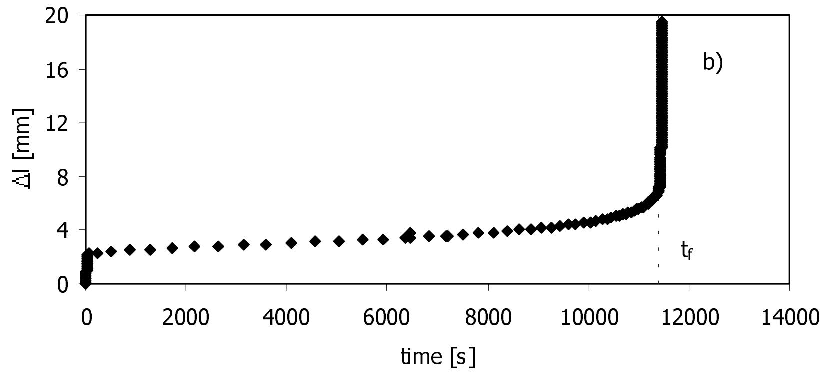


Fig. 1. Experimental creep curve: the dependence of the total elongation Δl of the specimen on the time of creep exposition t. The corresponding gauge length $L_0 = 36$ mm. a) smooth specimen, $\sigma_{\mathrm{nom}} = 300$ MPa, $t_{\mathrm{f,smooth}} \approx 1200$ s, b) C4 notched specimen, $\sigma_{\mathrm{nom}} = 300$ MPa, $t_{\mathrm{f}} \approx 12000$ s.

creep tests were performed under constant load regime in tension. The results of the measurements show that the dependency of the minimum creep strain rate $\dot{\varepsilon}_{\min}$ on the applied nominal stress related to the net section and corresponding to the steady state stage can be expressed in the form of the Norton law [15]

$$\dot{\varepsilon}_{\min} = B\sigma^n, \tag{1}$$

where $B = 5.7 \times 10^{-37}$ and $n = 12.94$ and $[\sigma] = \mathrm{MPa}$. Moreover, the time of creep exposition corresponding to primary and tertiary creep is negligible in comparison with the total lifetime of the specimen (Fig. 1).

Notch effects were studied using cylindrical bars with semicircular C-notches of differing radius ρ or semicircular V-notches with a wedge angle of 60°, a depth of D and a tip radius ρ (Fig. 2). Details of the geometry of the studied notches

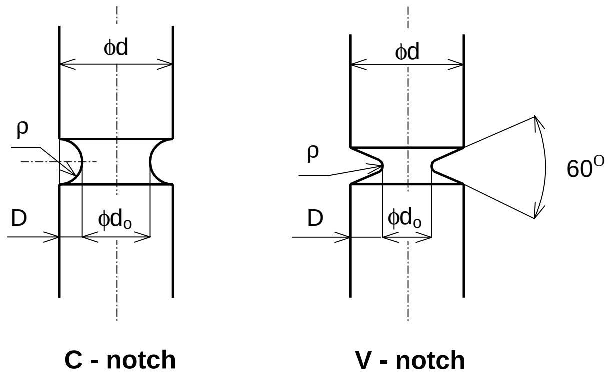


Fig. 2. Specimen geometry and geometry of the studied notches.

Table 1. Geometry of the notched specimens

Geometry of the specimens						Net stress
material	notch	ρ [mm]	ø d_0 [mm]	ø d [mm]	D [mm]	σ_{nom} [MPa]
P91	smooth	0	10	10	0	290
15313	smooth	0	8	8	0	200
P91	smooth	0	8	8	0	370
P91	C1	0.11	9.78	10	0.11	290
P91	C2	0.22	9.56	10	0.22	290
P91	C3	0.3	9.4	10	0.3	290
P91	C4	0.5	9	10	0.5	290
P91	C5	1	8	10	1	290
P91	C6	2	6	10	2	290
P91	C7	1.6	4.8	8	1.6	370
P91	C8*	0.5	7	8	0.5	370
15313	C8	0.5	7	8	0.5	200
15313	V1	0.14	7	8	0.5	200
P91	V2	0.156	5.68	8	1.16	370
P91	V3	0.43	4	8	2	370
P91	V4	0.2	8	10	1	290
P91	V5	0.2	6.8	10	1.6	290

and the value of the corresponding applied stresses are given in Table 1. The gauge length L_0 was 36 mm.

Generally, ductile creep rupture (and so the time to rupture t_{f}) is a function of material creep deformation characteristics as well as the component geometry. The creep behavior of the whole specimen can be described by the dependence of the total elongation of the specimen Δl on the time of creep exposition t. This is shown in Fig. 1a for the smooth specimen. No creep cracks were observed, and under given conditions ductile rupture is the dominant mechanism of fracture for both smooth specimens and notched specimens. In the case of notched specimens, the dependence Δl vs. t is of the same character (Fig. 1b), and the creep strain rises linearly with time until fracture occurs by necking at a finite time t_f [15–17]. The time to rupture t_f then corresponds to a rapid increase of strain on the elongation-time curve. The decisive part of the creep deformation (and so most of the lifetime) corresponds to the secondary creep stage and acceptable engineering calculations can be performed for P91 steel at 600 ℃ using the Norton law (1) only.

Let us denote by t_f time to rupture for a notched specimen and $t_\mathrm{f,smooth}$ the corresponding value obtained for a smooth specimen. For a constant net section stress, the value of the ratio τ (equal to $t_\mathrm{f}/t_\mathrm{f,smooth}$) is a measure of notch strengthening ($t_\mathrm{f}/t_\mathrm{f,smooth} > 1$) or notch softening ($t_\mathrm{f}/t_\mathrm{f,smooth} < 1$). The experimental results show the strong strengthening effect of pure creep loading for all types of notches [15], e.g., the lifetime of the bars with large notches was more than two orders of magnitude greater than for the smooth ones (Table 2).

T a b l e 2. The values of the calculated local and global coordinates corresponding to the studied notch geometry

Notch	Results of calculations					
	K_t	K_tplast	α_tip	$\bar{\alpha}$	$\bar{\dot{\varepsilon}}/\dot{\varepsilon}$	lifetime
smooth	1	1	1	1	1	1
C1	2.95	1.55	2.11	1.15	6.44E-01	1.8
C2	2.84	1.53	1.92	1.29	3.48E-01	3.1
C3	2.78	1.52	1.79	1.38	2.46E-01	4.5
C4	2.59	1.51	1.78	1.63	1.13E-01	10.6
C5	2.19	1.45	1.63	2.13	2.50E-02	55.8
C6	1.61	1.23	1.15	2.33	9.44E-03	113.3
C7	1.7	1.52	1.17	2.38	8.50E-03	382
C8*	2.5	1.49	1.67	1.76	7.13E-02	54.5
C8	2.5	–	1.67	1.76	2.90E-01	3.6
V1	3.9	–	1.78	1.86	2.13E-01	4.9
V2	4	1.79	1.77	2.55	6.92E-04	1247
V3	2.3	1	1.55	2.92	3.44E-03	4953
V4	4.23	1.98	1.75	2.33	1.56E-02	83.9
V5	4.32	1.95	1.78	3.11	2.19E-03	583

The strengthening effect of the notch can be attributed to the existence of a multiaxial stress state in the specimen. The change in the lifetime caused by a notch was found to be related to the properties of the material as well, but for the present paper only one material was studied, and the influence of the material on the lifetime was not taken into account.

3. Numerical approach

The calculations were carried out using an axial-symmetric model with the general purpose finite element system ANSYS [18] on a computer SGI. Eleven different notches were chosen for numerical calculations, see Table 1. Special attention was paid to the formulation of the boundary conditions. These correspond to the experimental set up used. The geometry of the whole specimen was used for the analysis, i.e., the influence of the length of the specimens and their grip in the testing machine were taken into account. Due to the symmetry of the specimens and the boundary conditions, only one quarter of the specimens was modelled. The eight node cylindrical symmetric elements PLANE82 were used for finite element modelling. The mesh size was refined until an elastic solution corresponding to the analytical one taken from [19] was obtained. Due to the finer mesh in the vicinity of the notch tip, the numbers of elements and nodes were relatively large, typically up to 400 elements and 800–1200 nodes.

Numerical analysis was performed for linear elastic theory, elastic-plastic conditions, and a continuously creeping material obeying relation Eq. 1, using the

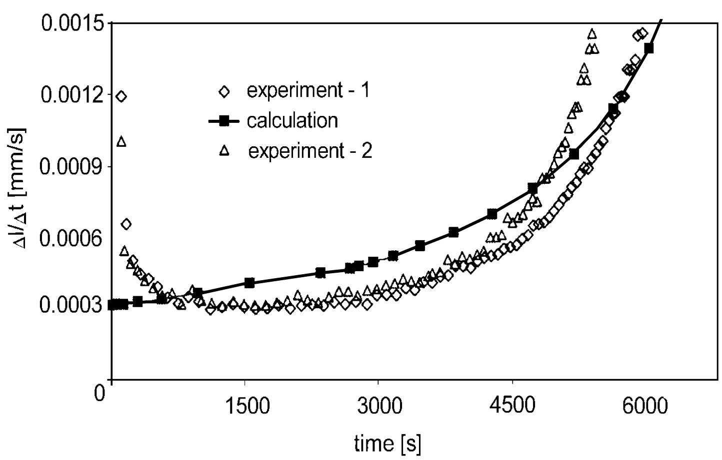


Fig. 3. Experimental and calculated dependency of $\Delta l/\Delta t$ vs. time t for C3 notched specimen and applied load $\sigma_{\mathrm{nom}} = 290$ MPa.

standard numerical procedures implemented in ANSYS. For all the calculations the standard options of the ANSYS system were used.

As a result of creep calculations, the displacement and corresponding distributions of creep strain and stress in the specimen as functions of time were found [15, 17].

To show how close presented calculations predict the experimentally observed behaviour of the notched specimens, the experimental and calculated dependencies of $\Delta l/\Delta t$ versus time t are shown in Fig. 3.

4. Results

As creep occurs in a notched body, the initial stress field redistributes at a rate which is controlled by the geometries of the notch and the specimen, the level of applied stress, properties of the materials, and the extent of the damage. In the following, all results presented correspond to secondary creep behavior, i.e., the Norton law Eq. (1) was used for calculations.

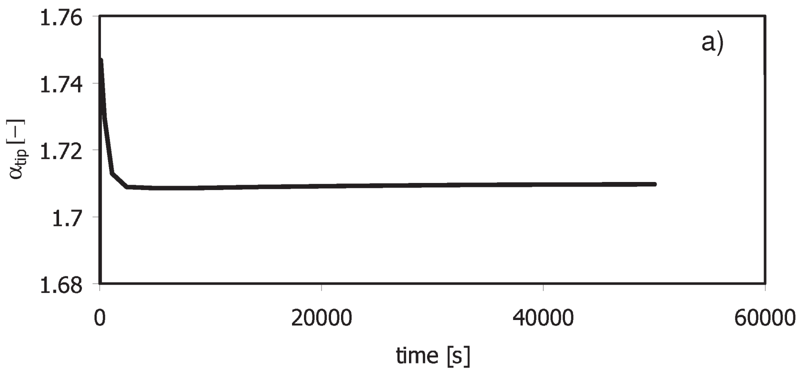
The results of creep calculations provide the distributions of stress, strain and displacement in the specimen under consideration as a function of time of loading t. The dependence of the total elongation of the specimen on the time of creep exposition were calculated for both smooth and notched specimens. In accordance with experiments, the calculated time to rupture t_{f} corresponds to a rapid increase of strain on the elongation-time curve. The values of $\tau = t_{\mathrm{f}}/t_{\mathrm{f,smooth}}$, i.e., the t_{f} estimated in this way normalized by the time to rupture of the smooth specimen at the same net stress $t_{\mathrm{f,smooth}}$ are given in Table 2 for all studied geometries of the notches.

The main feature of the results of numerical analysis is that the redistribution of stress after loading goes immediately after loading start and a stationary state is approached asymptotically in a relatively short time period (by comparison with time to rupture t_{f}). Due to the rapid redistribution of stress, the controlling variables for creep rupture correspond to those as calculated for a stationary state.

The stress multiaxiality due to the existence of the notch is quantified by the coefficient of the stress triaxiality α, corresponding to stationary state

$$\alpha = (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/\sigma_{\mathrm{eff}}, \tag{2}$$

where σ_{ij} are stationary values of the stress components, and σ_{eff} means the stationary value of the corresponding effective stress. As an example, the dependence of the coefficient of the stress triaxiality α_{tip} calculated at the notch tip on time t is presented in Fig. 4a. Analogously, the stationary values of other local variables determining the stress field around the notch tip were calculated and their values are summarized in Table 2.



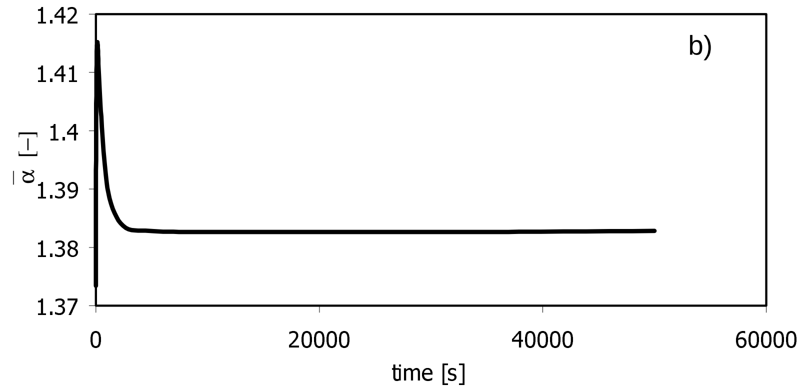


Fig. 4. Calculated dependency of the mean value of the stress triaxiality α (Eq. (2)) on time of creep exposition t. a) the local value α_{tip} calculated at the notch tip, b) the mean value $\bar{\alpha}$ calculated according to Eq. (3).

Note that no correlation exists between the time to rupture t_{f} (expressed equivalently as the ratio $\tau = t_{\mathrm{f}}/t_{\mathrm{f,smooth}}$) and the local parameters such as elastic stress concentration factor K_{tip}, plastic stress concentration factor K_{tplast} and stress triaxiality coefficient α_{tip} calculated at the notch tip (Table 2).

Ductile creep rupture is a function of the changes in gross geometric shape of a specimen, rather than an internal mechanism, and therefore quantities controlling the creep rupture do not have local character. In other words, to describe the influence of stress triaxiality on the fracture behavior of the notched specimens, global characteristics, calculated over the whole notch region, have to be used.

Creep rupture of notched specimens is due to plastic flow mainly in the notched section of the specimen. The application of the mean value of the stress triaxiality coefficient $\bar{\alpha}$

$$\bar{\alpha} = \frac{\int\int \alpha \mathrm{d}S}{S_0}, \tag{3}$$

calculated over the area of the original cross section in the notch region S_0 was suggested in [16]. In Fig. 4b, the dependence of the mean value of the stress triaxiality coefficient $\bar{\alpha}$ on the time t of creep exposition is shown. Again, the stationary value is reached within a short time interval.

In the present paper, the calculated mean value of the stress triaxiality coefficient $\bar{\alpha}$ corresponding to stationary state is correlated with the time to rupture $t_\mathrm{f}/t_\mathrm{t,smooth}$ for a wide variety of notch geometries.

The experimental fact that the creep strain for smooth specimens rises linearly with time until rupture occurs by necking implies that the creep strain rate remains constant during creep exposition (within the experimental scatter) constant as given by Eq. (1). It can be shown (see e.g. [20]) that the strain that would have been attained at time t_f, had the initial strain rate remained constant, is $1/n$ where n is the stress exponent (Eq. (1)). To a first approximation, this is taken as a practical measure of the usable strain available before the tensile specimen is overtaken by unstable accelerating deformations. It is accepted that the assumption holds as long as the stress state is uniaxial tension (i.e. for smooth specimen) and the time to rupture $t_\mathrm{f,smooth}$ is then easily found to be, e.g. [20],

$$t_\mathrm{f,smooth} = \frac{1}{nB\sigma^n} = \frac{1}{n\dot{\varepsilon}}. \tag{4}$$

Let us assume in the following that the controlling variable in the case of a multiaxial stress state (caused e.g. by the presence of a notch) is the mean value of the creep strain rate $\bar{\dot{\varepsilon}}$ calculated over the area S_0 in stationary state, i.e.,

$$\bar{\dot{\varepsilon}} = \frac{\iint \dot{\varepsilon} \mathrm{d}S}{S_0}. \tag{5}$$

Then analogously to the case of an uniaxial stress state, time for rupture of the notched specimen can be derived as

$$t_\mathrm{f} = \frac{1}{n\bar{\dot{\varepsilon}}}. \tag{6}$$

Using Eqs. (5, 6), the normalized values of the lifetime $t_\mathrm{f}/t_\mathrm{f,smooth}$ of notched specimens can be expressed as

$$t_\mathrm{f}/t_\mathrm{f,smooth} = \bar{\dot{\varepsilon}}/\dot{\varepsilon}, \tag{7}$$

where $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$ is the normalized creep strain rate. The calculated values of $\bar{\alpha}$ and $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$ for all types of studied notches are given in Table 2.

5. Discussion

The results presented in Table 2 were used to find a correlation between the time to fracture of smooth and notched specimens and the level of the stress multiaxiality in each specimen. With the aim to eliminate the influence of applied stress level, the time to fracture for notched specimens was divided by the time to fracture of the smooth specimen for the same loading conditions. It can be seen from Table 2 that there is no correlation between local quantities calculated at the notch tip and the lifetime of the notched specimens. The normalized values $t_\mathrm{f}/t_\mathrm{f,smooth}$ were then correlated with corresponding values of the mean value of stress triaxiality $\bar{\alpha}$ and $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$ calculated for stationary state.

The results obtained by calculations for studied notches and under given conditions show a fair linear correlation between the normalized time to rupture $t_\mathrm{f}/t_\mathrm{f,smooth}$ and value $\bar{\alpha}$ or $\bar{\dot{\varepsilon}}/\bar{\dot{\varepsilon}}_\mathrm{smooth}$ (Figs. 5 and 6). The experimental data $(t_\mathrm{f}/t_\mathrm{f,smooth})_\mathrm{exp}$ taken from [21] and given in Table 2 are shown in Figs. 5 and 6 as well and verify the calculated correlations.

It follows from the results presented that the lifetime of notched specimens is controlled by two parameters. The first one corresponds to applied load level and determines the lifetime $t_\mathrm{f,smooth}$ of the smooth specimen of the same geometry and corresponds to the value of the nominal applied load $\sigma = \sigma_\mathrm{nom}$ in Norton law (Eq. (1)). The second parameter expresses the influence of size and geometry of the notch and corresponds to the mean value of the stress triaxiality coefficient, $\bar{\alpha}$, calculated for stationary state. This value characterizes the degree of the notch strengthening and corresponds linearly with the ratio of the lifetimes $t_\mathrm{f}/t_\mathrm{f,smooth}$

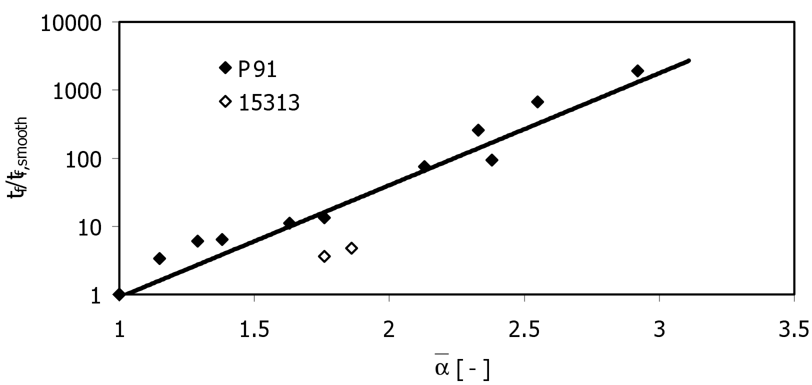


Fig. 5. Correlation between $t_\mathrm{f}/t_\mathrm{f,smooth}$ and $\bar{\alpha}$. The solid line corresponds to the calculated dependency for P91 steel. Experimental points are taken from [19]. Full points correspond to P91 steel, empty points to 2.25Cr-1Mo bainitic steel.

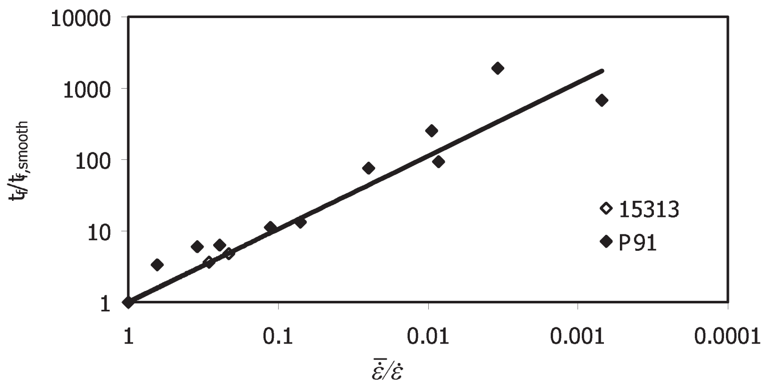


Fig. 6. Dependence of $t_{\mathrm{f}}/t_{\mathrm{f,smooth}}$ on $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$. The solid line corresponds to the calculated dependency. Experimental data are taken from [21]. Full points correspond to P91 steel, empty points to 2.25Cr-1Mo bainitic steel.

(Fig. 5). The correlation between $t_{\mathrm{f}}/t_{\mathrm{f,smooth}}$ and $\bar{\alpha}$ is material dependent, see empty points corresponding to 2.25Cr-1Mo bainitic steel in Fig. 5. Another possible method of expressing the influence of a notch on lifetime is to use the ratio $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$ of the average value of the creep strain rate calculated for the notched bar and normalized by the creep strain rate of the smooth specimen (i.e. corresponding to Norton law). The dependence of the normalized lifetime $t_{\mathrm{f}}/t_{\mathrm{f,smooth}}$ on the ratio $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$ is a function independent of material and notch geometry (Fig. 6).

It can be concluded that the application of the parameters of the global type, i.e., calculated as the mean values over the notch region makes it possible to introduce a two-parameter approach to lifetime estimation of the notched specimens. The knowledge of the second parameter, either the value of $\bar{\alpha}$ or the ratio $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$, makes it possible to predict the creep lifetime of notched specimens on the basis of creep data obtained on smooth specimens.

Note that the value of n in the Norton law (1) is high and for relatively high stress levels used (see Table 1) the rupture times are very short. The lifetime is dominated by a combination of large deformation and ductility exhaustion. The solved task is thus close to a viscoplasticity problem. The presented approach is a phenomenological one. On the other hand for low strain rates comparable to those that occur in design, the predominant mechanism of failure is continuum material damage where damage mechanics has to be used to predict rupture lives.

Note that instead of Eq. (1), another form of equation relating the dependency of the minimum creep strain rate $\dot{\varepsilon}_{\min}$ can be used in the procedure, see [15, 22].

6. Conclusions

(1) A method for the numerical simulation of the influence of the stress triaxiality on the lifetime of notched specimens under creep loading is described. The approach is applicable if the time of creep exposition corresponding to primary and tertiary creep is negligible in comparison with the total lifetime of the specimen.

(2) Linear correlations between normalized values of the lifetime $t_{\mathrm{f}}/t_{\mathrm{f,smooth}}$ and $\bar{\alpha}$ eventually $\bar{\dot{\varepsilon}}/\dot{\varepsilon}$ were found.

(3) A phenomenological two-parameter description of the notched specimen lifetime under creep was formulated.

(4) Based on the results obtained, the lifetime of the notched specimen can be estimated on the basis of creep data obtained on a smooth specimen.

The estimation of the lifetime of the notched specimen corresponding to the suggested procedure consists of the following steps:

(a) The basic material data corresponding to Eq. (1) have to be measured on smooth cylindrical specimens of studied material. These data create the input data for numerical simulations.

(b) The time to rupture, $t_{\mathrm{f,smooth}}$, of the smooth cylindrical specimen loaded by applied stress σ_{appl} has to be experimentally determined.

(c) For notched specimen and the net section stress corresponding to σ_{appl}, a numerical analysis for continuously creeping material obeying relation Eq. (1) has to be performed. As a result the displacement and the corresponding distributions of creep strain and stress in the notched specimen are obtained.

(d) Based on calculations performed, the mean value of the stress triaxiality coefficient $\bar{\alpha}$ (Eq. (3)) and the mean value of the creep strain rate $\bar{\dot{\varepsilon}}$ (Eq. (5)) are evaluated.

(e) The time to rupture, t_{f}, corresponding to the notched specimen is then given by Eq. (7), where $\dot{\varepsilon}$ corresponds to the creep deformation rate of the smooth specimen.

The validity of the presented results is limited to the high stresses and short lifetimes, where the controlling mechanism of rupture is a combination of large deformation and ductility exhaustion (e.g. necking).

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