Two-parameter description of creep/high-cycle-fatigue behaviour of notched 9% Cr steel
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Abstract

A notch effect under creep/high-cycle-fatigue loading conditions was studied both theoretically and experimentally in notched specimens of an advanced 9%Cr steel of the type P91 at 600°C. Experiments were performed under condition of the constant maximum net stress. The stress ratio R, i.e., the cyclic stress component of creep/fatigue loading was varied. The dependence of time to fracture on R exhibits nonmonotonous behaviour with a pronounced maximum coinciding with the fracture mode transition from pure creep to fatigue. The notched specimens show increased rupture strength when compared with smooth bars. The strengthening due to the notch depends on the notch geometry. It is shown that the notch tip stress triaxiality parameter is not sufficient to describe this phenomenon.

1 Introduction

The 9% Cr steel of P91 type is likely to be used under conditions of creep with superimposed fatigue loading. The literature data show a certain amount of knowledge about the behaviour of this steel subjected to a combination of creep and low-cycle fatigue, Yaguchi1. Relatively little work has been done in the creep/high-cycle-fatigue loading conditions. The behaviour of this material under conditions of mixed creep and high cycle fatigue loading at 600°C was investigated by Vašina2, using smooth specimens for the stress ratio $R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}}$ ranging from -1 to 1. For all these tests the maximum stress within the stress cycle was kept constant at $\sigma_{\text{max}} = 240$ MPa. The results of the study show that (i) both the lifetime and the creep rates depend on the stress ratio R, (ii) the mean stress appears to be the main parameter controlling the lifetime
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and the strain rate in the interval of $R$ for which degradation is caused mainly by creep, (iii) the process of fatigue damage is controlled by the applied stress amplitude (iv) the dependence of the lifetime on $R$ exhibits a broad, inexpressive maximum coinciding with the transition between the parts with prevailing creep and fatigue damage, respectively.

In many applications, structural components contain geometrical inhomogeneities, such as notches, that produce stress and strain concentrations under remote loading. Understanding notch behaviour is essential to the prevention of the failure of components and to the analysis of failures when these occur.

Notches are generally detrimental in cyclically loaded machine parts. The negative influence of a notch on the service life of a structure is most pronounced under conditions of high-cycle fatigue and becomes milder in the low cycle fatigue region. The fatigue limit of notched bodies is usually estimated by means of the theoretical (elastic) stress concentration factor $K_t$, defined as $\sigma_{\text{max}}/\sigma_{\text{nom}}$, where $\sigma_{\text{max}}$ is the maximum axial stress at the notch root and $\sigma_{\text{nom}}$ is the applied load divided by the smallest cross section. To describe the effect of notch triaxiality on the fracture behaviour of notches, another parameter, the notch tip stress triaxiality parameter $\alpha$, is usually used, e.g. Lukáš. The notch tip triaxiality parameter $\alpha$ is defined as

$$\alpha = \frac{\sigma_{xx} + \sigma_{yy} + \sigma_{zz}}{\sigma_{\text{eff}}} ,$$

where the values of the stress components are calculated for the vicinity of the notch tip. The fracture behaviour of notched bodies is then characterised by the two parameters. The parameter $K_t$ quantifies the size of the stress-strain field, and $\alpha$ indexes the effects of the geometry and the level of deformation on the tensile stress caused by different levels of triaxiality at the tip of the notch. This two-parameter fracture methodology assumes that the fracture behaviour of the test specimen is the same as that of structure, if both encompass the same value of $K_t$ and $\alpha$.

The experimental results confirm that the presence of a notch can either extend or shorten the creep life, referred to as notch strengthening or notch weakening effect, e.g. Eggeler. This effect depends on the notch type (different stress state near the notch root) and on the material, e.g. Penny.

The present paper reports a study of the notch effect under creep/high-cycle-loading conditions on type P91 steel. Further, two different notch geometries (but with the same $K_t$ and $\alpha$) are examined with the aim of testing the validity of the basic assumption of two-parameter fracture mechanics in the region of creep/high-cycle-fatigue.
2 Numerical analysis

The general purpose FEM program ANSYS\(^6\) was used for the computations presented in this study. The material was assumed to be elastic-plastic with a piece-wise linear approximation of the hardening behaviour taken from the cyclic uniaxial test results on smooth cylindrical specimens in the form of the corresponding cyclic stress-strain curve, see eqn (2). The material was assumed to obey the von Mises flow criterion with its associated flow rule and isotropic hardening behaviour. Finite strain formulation implemented in ANSYS was employed in all finite element calculations.

The finite element (FE) model applied to the numerical analysis used isoparametric quadratic eight-nodded (or six-nodded triangular) axisymmetric elements. Because of the axial symmetry of the geometry and load, only one-quarter of the specimens had to be modelled. Due to the finer mesh in the vicinity of the notch tip, the numbers of elements and nodes were large, typically about 2500 elements and 7000-8000 nodes. The accuracy of the FE modelling was checked by comparing the calculated values of \(K_t\) with those given in the literature, e.g. Peterson\(^7\).

Based on the results of the elastic analysis, two types of circumferentially notched cylindrical specimens with 8 mm diameter and with different notches geometries were suggested for measurement. The V-notched specimens (V-notch with a radius of 0.43mm, a depth of 2mm, and a wedge angle of 60°) and the specimen with the semicircular notch (SC-notched specimen with a notch of radius 0.5mm). The geometry both notches was designed so that the value of \(K_t\) was 2.5 and that of \(\alpha\) 1.4.

Further, the distribution of stress and strain was found for the suggested notched specimens for elastic, elastic-plastic and creep loading conditions.

3 Material and experimental procedure

Tempered martensite ferritic steel with following heat treatment was used: austenitisation at 1060°C for 1 h, then quenching and tempering for 2 h at 750°C. The corresponding mechanical properties at room temperature were \(R_{p0.2} = 560\) MPa, \(R_m = 710\) MPa.

Determination of the lifetime of notched specimens under creep/high-cycle-fatigue loading was performed on a modified resonant pulsator under load control. The maximum load was selected (from practical reason) in such a way that the longest lifetime did not exceed 10\(^5\) s. So the corresponding maximum stress on the beginning of the test was 370 MPa. Specimens were placed in an electric furnace in laboratory air. The desired temperature 600°C was reached within one hour at controlled zero load. After three hours delay for temperature stabilisation the mean load was applied. After the desired mean load had been reached, the resonant system was switched on, and the prescribed cyclic stress component was reached smoothly over the first 500 cycles. The frequency of cyclic loading was 120 Hz. Specimens were tested up
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to their final fracture. The elongation of specimen gauge length was monitored continuously.

The tensile creep tests of smooth specimens of 5 x 3.2 mm were performed in standard creep machines operating under constant load at 600°C. The changes in specimen length were measured using linear variable differential transducers, whose output was recorded continuously.

The resonant fatigue system Amsler was used to determine the cyclic stress-strain curve at 600°C in the region of high-cycle-fatigue. Tests were performed under controlled plastic strain. The cyclic stress-strain curve was determined using the fatigue softening curves for the number of cycles corresponding to half the lifetime.

4 Results and discussion

The experimentally determined cyclic stress-strain curve was approximated by the following power-law equation

$$\sigma_a = A \varepsilon_{ap}^n$$

where \( A = 497 \) MPa and \( n = 0.118 \).

Figure 1 shows the results for creep/high-cycle-fatigue in terms of the dependence of the lifetime \( t_f \) on the stress ratio \( R \) for both V-notched and SC-notched specimens. Note that in all cases the maximum stress \( \sigma_{max} \) was kept constant at 370 MPa. The dependence of the lifetime \( t_f \) on the \( R \) ratio exhibits a pronounced maximum for both types of notch. Starting with pure creep (\( R = 1 \)), the increasing cyclic stress component (decreasing the \( R \) ratio) results in the increase of lifetime to a maximum at \( R = 0.7 \). This value is nearly the same for both curves. The lifetime of notched specimens on the right hand side of the maximum seems to be determined predominately by the creep mechanism, i.e., the final fracture do not show any fatigue crack initiation and propagation. Necking and ductile fracture is observed. The maximum value of \( R \) is connected with the transition of the fracture mode. The typical ductile creep fracture is replaced by a fracture caused by fatigue. The left hand side part of the \( t_f \) vs. \( R \)
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dependence is characterised by lifetime decrease. This is more pronounced for V-notched specimens. In the region where the creep mechanism prevails, the lifetime of V-notched specimens is about 25 - 100 times greater than that of SC-notched specimens.

Finally, the experimentally determined dependence of the time to fracture \( t_f \) on the stress for pure creep in smooth specimens is presented in Figure 2. The full line corresponds to the fitted equation

\[
t_f = 1.4 \times 10^{30} \sigma^{-11},
\]

where \( \sigma \) is in MPa and \( t_f \) in s.

Let us discuss the pure creep case (\( R = 1 \)) at first. According to eqn. (3) the lifetime of smooth specimens for \( \sigma_{\text{mean}} \) used in our creep/fatigue experiments (i.e., \( \sigma_{\text{mean}} = 370 \) MPa) is extremely short, namely, \( t_f = 83 \) s. Comparing this with the corresponding experimental values for notched specimens (see Figure 1) leads to the conclusion that both notches have a strong strengthening effect. The lifetime for SC-notched specimens is 25 times higher, for V-notched specimens even 660 times higher.

To explain the change in the lifetime due to the presence of the notch, let us take into account the stress redistribution caused by the notch, see Figure 3. In the cases of both notches, there is a localised increase in the stresses in the vicinity of the notch tip (in comparison with \( \sigma_{\text{mean}} \)) and the decrease of the stress in the region around the centre of the specimen. Presuming that the minimum value of the axial stress component \( \sigma_{zz} \) is the variable controlling the lifetime, and applying the eqn (3), we get simply \( t_f = 1500 \) s for the V-notched specimen and \( t_f = 410 \) s for the SC-notched specimen. Both values are lower than the experimentally determined values (\( t_f = 5.5 \times 10^4 \) s for the V-notched specimen and \( t_f = 2 \times 10^3 \) s for the SC-notched specimen, see Figure 1). Thus the notch strengthening effect cannot be explained simply by the redistribution of stress alone, and, in accordance with Penny\(^5\), the change in the lifetime caused by the presence of notches is found to be rather a material property - but no general conclusion can be drawn.
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Figure 3: The calculated stress distribution in the cross section of notched specimens. $r$ is the distance from the notch tip. $r = 2$ mm corresponds to the centre of the specimen for the V-notch, $r = 3.5$ mm corresponds to the centre of the specimen for the SC-notch. Solid lines correspond to stress distribution in the V-notched specimen, dashed lines to those for the SC-notched specimen. Curves 1,2,3 correspond to the stress components $\sigma_{zz}$, $\sigma_{tt}$ and $\sigma_{rr}$, respectively. The stress component $\sigma_{zz}$ is equal to zero. The stress values correspond to the initial state of creep loading, i.e., to elastic-plastic solution.

Figure 4: The distribution of the stress triaxiality parameter $\alpha$, calculated according to eqn (1) over the cross sections of the notched specimens. $r$ is the distance from the notch tip. Solid lines correspond to the V-notched specimen, dashed lines hold for the SC-notched specimen. Curves 1 correspond to the elastic case, curves 2 hold for the elastic-plastic solution. The values of the notch tip triaxiality correspond to $r = 0$. 
The difference between the lifetime of the V- and SC-notched specimens can be, at least partly, attributed to different states of triaxiality over the bulk of the specimens. The V-notched specimen has a low degree of triaxiality for the major part of the cross section; the high stress triaxiality is limited to the vicinity of the notch tip, see Figure 4. On the other hand, for the SC-notched specimen, the whole cross section is a region with a high degree of the stress triaxiality. In contrast to the mechanism of damage caused by fatigue, the mechanism of damage caused by creep depends on the distribution of stress and strain over the entire cross section of the specimen. Thus the different fracture behaviour of the two specimens cannot be described by means of the localised distribution of stress and strain in the vicinity of the notch tip (which is characterised by notch tip triaxiality $\alpha$). The level of stress triaxiality over the entire cross section of the specimen is the decisive factor in determining the creep behaviour. The proper variable describing the degree of triaxiality and its influence on the fracture behaviour under creep/high-cycle-fatigue conditions could be the average value of the stress triaxiality $\alpha$ over the entire cross section of the specimen, i.e.,

$$\alpha_{\text{mean}} = \frac{1}{S_0} \int \alpha \, dS,$$

where $S_0$ is the area of the cross section.

For smooth specimen, $\alpha_{\text{mean}} = 1.0$, for the SC-notched specimen, $\alpha_{\text{mean}} = 1.6$, and for the V-notched specimen, $\alpha_{\text{mean}} = 3.6$. We suggest using $\alpha_{\text{mean}}$ values to measure the triaxiality in cases where the damage is (partly or completely) caused by creep.

In the region where the prevailing mechanism is fatigue crack initiation and propagation (i.e., for $R < 0.7$), the fracture behaviour is given by the local stress and strain field in the vicinity of the notch tip. Thus the controlling variables here are the stress amplitude (described by the stress concentration factor $K_i$) and the parameter of the notch tip stress triaxiality $\alpha$.

## 5 Conclusions

Creep/high-cycle-fatigue tests were carried out on cylindrical specimens of martensite ferritic 9%Cr steel (P91) containing two geometrically different types of circumferential notches. The main results can be summarised in the following way:

1) The investigated steel showed substantially increased rupture when notches were present. This notch strengthening effect cannot be explained by the redistribution of stress alone.

2) The dependence of the lifetime $t_f$ on the stress ratio $R$ for notched specimens had features qualitatively similar to those for smooth specimens, but the values of $t_f$ were quite different.

3) The effect of a notch on the lifetime depends strongly on the geometry of the notch. The influence of triaxiality on the lifetime cannot be determined.
by using only the local value of the notch tip stress triaxiality \( \alpha \). It is suggested that mean value of the parameter \( \alpha \), namely \( \alpha_{\text{mean}} \), calculated over the whole cross section of the specimen, can be used as a measure of the triaxiality.

References


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