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Evaluation of fatigue crack initiation in a notched single-crystal superalloy component

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Abstract

The fatigue crack initiation in a notched single-crystal nickel-base superalloy component at 500°C was investigated and analysed. A critical plane approach in combination with a critical distance method has been adopted, in which the total shear strain ranges on the discrete slip planes are evaluated. Furthermore, a Coffin-Manson type of expression is used to predict the number of cycles to fatigue crack initiation. The experimental test specimens were studied by microscopy to determine on which crystallographic plane the fatigue initiation occurred. A good correlation between the experimental results and the simulated results were found.

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Keywords: Single-crystal superalloy; Fatigue crack initiation; Critical plane approach; Notch correction; Critical distance theory

1. Introduction

Most gas turbine blades have a variety of features like holes, interior passages, curves and notches, which may raise the local stress/strain level to the point where plastic flow occurs. The state-of-the-art materials used for the first stage of the gas turbine blading are single-crystal nickel-base superalloys, which have excellent mechanical properties in very hot environments [1]. These alloys have a face-centered-cubic (FCC) crystal structure, with well defined slip planes. However, the elastic and plastic anisotropy of the single-crystal material makes the prediction of the fatigue life rather complex.

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In a low cycle fatigue (LCF) context, cyclic loading of a single-crystal component will give rise to plastic flow along the slip planes and eventually persistent slip bands (PSB) will start to appear, which will act as fatigue crack initiation locations, see e.g. Suresh [2]. Thus, it is physically motivated to make use of these planes in a critical plane context. Many different critical plane approaches have been proposed; see e.g. [3] or [4]. As an example, both Arakere et al. [5] and Naik et al. [6] investigated single-crystal superalloys exposed to high cycle fatigue (HCF) by using the critical plane approach, obtaining good agreement with experimentally obtained fatigue initiation data.

In a notched component the local stress/strain level is much more inhomogeneous than in a smooth component, due to the stress/strain concentration of the notch. A useful approach, when handling the notch gradients, is the theory of critical distances, see e.g. [7] or [8]. By using the Point Method (PM), failure is assumed to take place when the stress reaches the plain fatigue limit \( \sigma_0 \) at a certain distance underneath the notch surface. Thus, the local high stress/strain gradient at the notch is handled by using a lower stress/strain level in the evaluation of the fatigue life of the notched structure. To handle medium cycle fatigue Susmel et al. [9] argued that the critical distance should be a function of the number of cycles to failure. However, in a recently published paper by Susmel et al. [10] they expand the theory of critical distances into the elastoplastic regime to handle LCF. Here, they claim that the critical distance is a material property, independent of the notch geometry, loading and number of cycles to failure.

2. Experiments

The seven investigated test specimens made of the single-crystal nickel-base superalloy MD2, see [11], were machined from cast bars with their longitudinal axes nominally parallel to the \([001] \) crystal direction. The deviation (\( \theta \)) from the ideal \([001] \) orientation varied between 0.3° and 11.7° for the specimens, and is listed in Table 1 for each specimen. The stress-strain response during cyclic loading, with \( R = \varepsilon_{\text{min}}/\varepsilon_{\text{max}} = 0 \), was investigated using a 100 kN servo-hydraulic testing machine. The tests were conducted at 500°C under displacement control with the extensometer symmetrically attached over the notch. The nominal strain ranges are listed in Table 1. The number of cycles to fatigue crack initiation was determined from optical inspections of the notch by use of a CCD-camera.

Table 1. Number of cycles to fatigue crack initiation, applied strain range and deviation for the different test specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta (\degree) )</td>
<td>4.0</td>
<td>6.4</td>
<td>0.3</td>
<td>6.1</td>
<td>11.7</td>
<td>7.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Strain range (%)</td>
<td>0.5</td>
<td>0.4</td>
<td>0.45</td>
<td>0.55</td>
<td>0.491</td>
<td>0.537</td>
<td>0.598</td>
</tr>
<tr>
<td>Cycles, ( N_{\text{exp}} )</td>
<td>622</td>
<td>3164</td>
<td>1834</td>
<td>507</td>
<td>924</td>
<td>530</td>
<td>334</td>
</tr>
</tbody>
</table>

Table 2. The predicted number of cycles to fatigue crack initiation for the test specimens (without notch correction)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles, ( N_{\text{sim}} )</td>
<td>48</td>
<td>256</td>
<td>182</td>
<td>5</td>
<td>87</td>
<td>43</td>
<td>5</td>
</tr>
</tbody>
</table>
3. Modelling

In this paper the constitutive model presented by Leidermark et al. [12] has been used. This model is based on crystal plasticity and takes Schmid as well as non-Schmid stresses, elastic anisotropy and tension/compression asymmetry into account. To model the LCF behaviour of smooth single-crystal test specimens Leidermark et al. [11] made use of the critical plane approach. In this model a life function based on the total shear strain range, which follows a Coffin-Manson type of expression, with the following structure was employed

\[ \Delta \gamma_{\text{tot}}^{\text{max}} = a \left( N_i \right)^b \]  

(1)

where the constants \( a = 0.031 \) and \( b = -0.122 \), determined from twelve experiments of smooth test specimens subjected to uniaxial cyclic loading in the nominal [001], [011] and [T11] crystal orientations with \( R_I = -1 \), were found to give a good correlation to all tests.

4. Analyses and results

FE-simulations of the seven notched test specimens were carried out by the software LS-DYNA version 971, by using the \( \kappa \)-values and the elastic data stated in [11]. Furthermore, the deviation in orientation and the applied strain range for each test specimen were taken into consideration. The maximum total shear strain range was determined for each test specimen by examining all crystallographic slip systems in all the surface elements of the arched part of the notch. The number of cycles to fatigue crack initiation predicted by Eq. (1) in the simulations (without notch correction) can be found in Table 2. By plotting the simulated number of cycles to fatigue crack initiation (without notch correction) versus the experimentally obtained lives, see Fig 1a, it can clearly be seen that a too conservative fatigue initiation life is predicted.

4.1. Notch correction

The theory of critical distances is used to evaluate the strain responses in the notch to find a satisfying fatigue crack initiation life. Furthermore, a critical distance that is dependent on the number of cycles to initiation is used. In each simulation, at the location where the maximum total shear strain range is found by the above technique and orthogonally inwards to a distance of five elements, the total strain range was plotted versus the distance into the notch, \( r \). As one-point integration is used the strain range on the critical plane is extracted from the midpoint of each of these five elements and the same applies for the distance with reference to the notch surface. The critical plane is allowed to change in the different elements. A power law function for each simulation is defined from a curve fit of the respective points according to

\[ \Delta \gamma_{\text{tot}}^{\text{crit}} = e_k r^{f_k}, \quad k = 1, \ldots, 7 \]  

(2)

where \( k \) is the number of the corresponding simulation. The values of \( e_k \) and \( f_k \) can be seen in Table 3. To determine the critical distance in each simulation the corresponding fatigue initiation life from the respective experiment \( N_{\text{exp}} \) was inserted into Eq. (1) to give a strain range. This strain range is then used in Eq. (2) to find the corresponding experimental critical distance. In this analysis, the Point Method was
used, hence the critical distance $r_{\text{exp}}$ is the intersection point between the curve and the obtained strain range, see Table 3 for the distances.

Table 3. The critical distances for each specimen

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_k$</td>
<td>0.001225</td>
<td>0.001182</td>
<td>0.001608</td>
<td>0.0009526</td>
<td>0.0009754</td>
<td>0.001184</td>
<td>0.000952</td>
</tr>
<tr>
<td>$f_k$</td>
<td>-0.3036</td>
<td>-0.2865</td>
<td>-0.2578</td>
<td>-0.3610</td>
<td>-0.3222</td>
<td>-0.3107</td>
<td>-0.3605</td>
</tr>
<tr>
<td>$r_{\text{exp}}$ (mm)</td>
<td>0.3199</td>
<td>0.3496</td>
<td>0.3664</td>
<td>0.5347</td>
<td>0.2919</td>
<td>0.3235</td>
<td>0.4586</td>
</tr>
</tbody>
</table>

To obtain a cycle dependent critical distance relation the experimentally obtained number of cycles to initiation is plotted versus the corresponding critical distances obtained by the simulations. By using the following relation, proposed by Susmel et al. [9]

$$N_i = cr^d$$

we obtained $c=6.6647 \times 10^{-9}$ and $d=-3.2183$, when a curve fit was performed to the specific points. Now, to determine the fatigue crack initiation life of the simulated notched test specimens, the following non-linear equation system needs to be solved for each of the seven simulations

$$\begin{align*}
\Delta \gamma^{\text{tot}} &= a\left(N_i\right)^b \\
N_i &= cr^d \\
\Delta \gamma^{\text{tot}} &= e_k r^f s, \ k = 1, \ldots, 7
\end{align*}$$

with a starting point in $N_{i,0} = (\Delta \gamma^{\text{tot}}/a)^{1/b}$, where $\Delta \gamma^{\text{tot}}$ was taken from the element at the notch surface which experiences the highest strain range. The obtained fatigue crack initiation life and the critical plane found at the critical distance can be seen in Table 4 for all simulations, and the predicted fatigue crack initiation lives versus the experimental ones can be seen in Fig 1b.

Fig. 1. Comparison between the experimentally obtained and predicted fatigue crack initiation life; (a) without notch correction and (b) with notch correction
Table 4. The fatigue crack initiation life and critical plane for the simulations with notch correction

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles, (N_{\text{sim}})</td>
<td>798</td>
<td>1792</td>
<td>1251</td>
<td>353</td>
<td>1216</td>
<td>719</td>
<td>359</td>
</tr>
<tr>
<td>Critical plane</td>
<td>((\overline{1}11))</td>
<td>((\overline{1}11))</td>
<td>((1\overline{1}1))</td>
<td>((1\overline{1}1))</td>
<td>((\overline{1}11))</td>
<td>((1\overline{1}1))</td>
<td>((\overline{1}11))</td>
</tr>
</tbody>
</table>

An error factor \(f_{\text{err}}\) was determined for each of the presented figures in Fig 1, defined by the following expression

\[
\log f_{\text{err}} = \max_{1 \leq k \leq 7} \left| \log N_{\text{exp}, k} - \log N_{\text{sim}, k} \right|
\]

The error factor for the case of no notch correction is 92.1, which is not a satisfying result. When one looks at the case with notch correction one sees that the numbers of cycles to failure are aligned around the diagonal and that the error has been lowered to a factor of 1.8.

4.2. Microscopy

After the uniaxial cyclic testing, the test specimens were force opened and analysed by microscopy to determine which crystallographic plane(s) the crack had initiated on in each specimen, see Fig 2 for the microscopy images. From these one can clearly see that the crack initiation is located on a crystallographic plane, hence motivating the use of the crystallographic planes as potential critical planes in the critical plane approach. The angle of the initiation planes were measured and the corresponding crystallographic planes were determined, see Table 5. In test specimen N3 it was found that the initiation occurred on two slip planes. The deviation in orientation is only 0.3° in this specimen, hence nearly perfect with the nominal load direction \([001]\).

Table 5. Crystallographic plane which the test specimens initiated on

<table>
<thead>
<tr>
<th>Specimen</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>N4</th>
<th>N5</th>
<th>N6</th>
<th>N7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane</td>
<td>((\overline{1}11))</td>
<td>((\overline{1}11))</td>
<td>((\overline{1}11), (1\overline{1}1))</td>
<td>((\overline{1}11))</td>
<td>((\overline{1}11))</td>
<td>((1\overline{1}1))</td>
<td>((1\overline{1}1))</td>
</tr>
</tbody>
</table>

Fig. 2. The force opened test specimens, showing the crystallographic plane which they initiated on
5. Discussion and concluding remarks

From the results it can be seen that the above presented technique can be used to predict the fatigue crack initiation lives with great satisfaction. Furthermore, it was found by microscopy that this procedure enables to correctly predict on which crystallographic plane the fatigue initiation occurs, disregarding negative normal directions. The only exception is specimen N6, in which the corresponding critical plane is not correctly predicted, even though the two neighbouring elements gave a good match. A source of error can be the mesh density, as the strain range and distance are evaluated in the midpoint of the elements, one might get another initiation plane if the element size is smaller or bigger. Anyway, a main conclusion that can be drawn on the basis of the work performed in this paper is that the critical plane approach in combination with the theory of critical distances has a potential for use in predicting the LCF fatigue crack initiation of single-crystal nickel-base superalloy components.

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