A study of creep-fatigue interaction in a new nickel-based superalloy

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Abstract

The behaviour of creep-fatigue interaction of a new nickel-based superalloy has been described using the Chaboche unified model. Simple cyclic and dwell experiments have been carried out at three strain rates at 650°C. The optimised material parameters have been determined by a simultaneous numerical (non-linear least-square) approach as well as a step-by-step procedure using basic material data, and applied to dwell tests. The predictive capability of the Chaboche model for this alloy will be evaluated.

Keywords: unified constitutive models, parameter determination, non-linear least-square optimisation, creep-fatigue interaction, nickel-based superalloy.

1 Introduction

A new nickel-based superalloy has been developed at Rolls Royces plc via a power metallurgy route for turbine disc application. The alloy is solution treated following by an oil quench and duplex aging treatments to meet the increasing demands for higher efficiency and thrust to weight ratios. Compared with conventional cast and wrought nickel-based superalloys, this alloy provides some superior mechanical properties, in particular high tensile strength and creep resistance at elevated temperature up to 700°C. It is necessary to conduct the stress analysis and life prediction of this alloy at high temperature and cyclic loading conditions, some evaluation work [1-5] of this new alloy has been done since 1996 in our group. In this paper, we will aim at one of the fundamental problems: creep-fatigue interaction. The deformation under combined creep and fatigue loading conditions can not be dealt with using either time-dependent (creep) or time-independent (fatigue) models. Stress relaxation during dwell
periods is a typical problem involving both time-dependent and time-independent deformation. Our objective of the present study is to develop a viscoplastic constitutive model that could accurately describe the stress relaxation behaviour under the cyclic dwell loading conditions as well as other inelastic behaviours.

For rate-dependent plastic deformation, a number of constitutive models have been proposed and developed by Miller [7], Walker [8], by Krempl E [9], by Ohno N. and Kachi Y. [10] and by Chaboche [11]. In recent years, the unified Chaboche model has attracted much attention due to its capacity in modelling a wide range of inelastic material behaviour such as cyclic hardening/softening, Bauschinger effect, stress relaxation, stress ratchetting and creep for a range of materials including stainless steels and nickel-based superalloy [12]. In this paper, the basic Chaboche model [11] was adopted and modified in the description of cyclic plasticity and viscoplasticity of this new nickel-based superalloy. An optimisation method [3,4,6] of the parameter evaluation based on the Levenberg-Marquardt algorithm has been developed utilizing the monotonic, cyclic, relaxation and creep test data obtained at 650°C. The numerical results will be compared with the experimental results.

2 Experimental description

The experimental results were obtained in the newly developed nickel-based superalloy [3]. Smooth specimens with a diameter of 6.9mm and gauge length of 12.5 mm were used for the experiments. An Instron 8500 servo-hydraulic testing machine was used with computer controlled loading spectra programmed as required. An electric resistance furnace was used with the temperature controlled at 650 ± 2°C. An extensometer (12.5+2.5/-1.25mm) was used to monitor the strain.

The uniaxial strain controlled cyclic and dwell tests were carried out at 650°C for three strain rates: 0.5%/s, 0.05%/s, 0.005%/s. The comparison of the saturated loops for the cyclic and dwell tests (with 100s strain hold) at 0.5%/s and 0.005%/s strain rates is shown in the Figure 1. It is obvious that the enlarged $\Delta \varepsilon_p$ occurred for the dwell tests compared with the simple cyclic tests. When the strain hold time was 10s, no distinct difference in $\Delta \varepsilon_p$ was observed between the simple cyclic and the dwell test at 0.05%/s (results omitted).

3 Determination of material parameters

The uniaxial form of the Chaboche model adopted here is from Chaboche and Rousselier [11] without the plastic strain range memorization (detailed in Appendix I). The model in its present form contains ten materials. These are Young’s modulus $E$; kinematic hardening parameters $a_1, a_2, C_1, C_2$;
isotropic hardening parameters $Q$ and $b$, viscous parameters $Z$, $n$ and initial size of the yield surface $k$. These parameters need to be determined from a suitable set of experimental data.

![Figure 1: Comparisons of the saturated loops of the cyclic and dwell tests.](image)

The identification of the material parameters begins with a step-by-step procedure to obtain an initial set of parameters [7]. These initial parameters and the test database including the monotonic, simple cyclic at three strain rates (0.5%/s, 0.05%/s, 0.005%/s), and creep tests are used as inputs in the simultaneous identification procedure to obtain an optimum set of parameters. The essence of this method is seeking a global minimum in the difference between the numerical and the experimental observable such as stress or strain. In this work, the difference between the values of stress/strain from the numerical analyses and the experiments were represented in an objective function:

$$ F = \frac{1}{2} \sum_{i}^{N} \sum_{j}^{M} W_{ij} (Y_{ij}^{num} - Y_{ij}^{exp})^2 $$  \hspace{1cm} (1)
where $Y_{ij}^{num}$ and $Y_{ij}^{exp}$ represent the numerical and the measured stresses/strains respectively. $N$ is the total number of experiments and $M$ is the total number of data points in the $i$th experiment. A weight factor was introduced to ensure the equal contribution from each type of the experimental data, irrespective of the number of the data points in each experiment. Details of the optimisation procedure are given elsewhere [4, 7].

The initial and the optimised parameters are presented in the table 1, the Young’s modulus $E = 193000$ MPa. For the optimised parameters, a statistical analysis has also been carried out to evaluate the quality of the parameters. Given a threshold of 0.67 there is no undesirable correlation between the parameters apart from those due to the structure of the formulation.

### Table 1: Material parameters estimated.

<table>
<thead>
<tr>
<th></th>
<th>Initial parameters</th>
<th>Optimise parameters</th>
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</thead>
<tbody>
<tr>
<td>$b$</td>
<td>5.54</td>
<td>8.67</td>
</tr>
<tr>
<td>Q (MPa)</td>
<td>154.0</td>
<td>142.45</td>
</tr>
<tr>
<td>$a_1$ (MPa)</td>
<td>33.17</td>
<td>306.41</td>
</tr>
<tr>
<td>$C_1$</td>
<td>1210.0</td>
<td>276.44</td>
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<tr>
<td>$a_2$ (MPa)</td>
<td>614.69</td>
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</tr>
<tr>
<td>$C_2$</td>
<td>395.0</td>
<td>1926.05</td>
</tr>
<tr>
<td>$Z$ (MPaS$^{1/6}$)</td>
<td>607.89</td>
<td>564.49</td>
</tr>
<tr>
<td>$n$</td>
<td>18.149</td>
<td>27.53</td>
</tr>
<tr>
<td>K (MPa)</td>
<td>150.0</td>
<td>126.95</td>
</tr>
</tbody>
</table>

### 4 Results and discussion

The simulated results of dwell tests using the optimised material parameters are compared with those obtained experimentally. Figure 2 presents the comparison of the saturated loops of the dwell tests with 100s hold at 0.05%/s (strain range: 1.6%) and 0.005%/s (strain range: 2.0%) strain rates. Figure 3 and 4 present the stress relaxation curves of the saturated cycles of the dwell tests at 0.05%/s and 0.005%/s strain rates individually. Figure 5 describes the evolution of the stress amplitudes of the dwell tests at 0.05%/s and 0.005%/s. Figure 6 presents the comparison of simulated and experimental of creep test at three stress levels. From these figures, the simulated and experimental results seem to compare well with each other, which indicates that Chaboche model is capable of describing the stress relaxation behaviour during holds in dwell tests.
Figure 2: Comparison of simulated and experimental results of the saturated loops of the dwell tests (0.05%/s, 0.005%/s).

Figure 3: Comparison of the simulated and experimental results of the stress relaxation of the dwell test (0.05%/s).
Figure 4: Comparison of the simulated and experimental result of the stress relaxation of saturated cycle for the dwell test (0.005%/s).

Figure 5: Comparisons of simulated and experimental results of the stress amplitude for the dwell tests (0.5%/s and 0.005%/s strain rates).
Figure 6: Comparisons of simulated and experimental results of creep tests.

5 Closing remarks

Based on the representative experimental data obtained from carefully controlled experiments, the initial and the optimised parameters were obtained for a nickel-based superalloy. The simulation using the optimised parameters offers much improved results compared with our early results [2,3] on conventional and advanced nickel-based superalloys. Given the fact that virtually the same optimisation procedure has been followed in all the work presented, the significance of the quality of the experimental data cannot be over-emphasised. Only data from the simple cyclic tests were used in the optimisation. Since the optimiser was based on a gradient approach that seeks the “deepest descent”, the closeness of the initial parameters to the optimised parameters is important to ensure fast and reliable convergence.

Apart from the creep curves, the simulated results compare well with those obtained experimentally. Significantly improved response has also been obtained in creep cases up to the tertiary regime. This is particularly notable as no additional parameters have been introduced and no undesirable correlations have been identified. The prediction of dwell behaviour (up to 100s hold) was based on the parameters obtained from the simple cyclic tests. This has demonstrated the capacity of the model in the description of creep-fatigue interaction.
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Appendix I: The Chaboche unified model adopted in this work

\[ \dot{\varepsilon}_p = \left( \frac{f}{Z} \right)^n \text{sgn}(\sigma - \chi) \]  (A1)

where \( \text{sgn}(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases} \) and \( \langle x \rangle = \begin{cases} x, & x \geq 0 \\ 0, & x < 0 \end{cases} \)

\[ f = J(\sigma - \chi) - R - k \leq 0 \]  (A2)

\[ J(\sigma - \chi) = |\sigma - \chi| \]  (A3)

\[ \chi = \chi_1 + \chi_2 \]

\[ \chi_i = C_i (a_i \dot{\varepsilon}_p - \chi_i \dot{p}) \quad i = 1, 2 \]  (A4)

\[ \dot{p} = |\dot{\varepsilon}_p| \]

\[ \dot{R} = b(Q - R) \dot{p} \]  (A5)

References


