AN ANALYTICAL PROCEDURE TO INCORPORATE THE BAUSCHINGER EFFECT ON FRETTING FATIGUE MODELS

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ABSTRACT

This paper proposes a modification on SWT model concerning the prediction on fretting fatigue life, in order to take into account the material deviation from the ideal elastic-plastic behaviour, the so-called “Bauschinger effect”.

The possible consequences of the Bauschinger effect on fretting fatigue life and mainly in fretting fatigue initiation are discussed. It is proved that Bauschinger parameter incorporated into the SWT model substantially improves the fretting fatigue predictions.

KEYWORDS: Bauschinger effect, fretting fatigue, Al7175 and CK45 alloys.

1. INTRODUCTION

Fretting fatigue occurs at the interface between two contacting bodies that are pressed against each other in the presence of cyclic loads that gives rise to a small relative displacement. Fretting fatigue is the most damaging aspect of fretting that leads to early cracking and shorter life relative to the plain fatigue situation. Under fretting fatigue conditions, fatigue strength or endurance limits can be reduced by as much as 50 to 70% during fatigue testing.

Fretting fatigue is encountered in many applications fields, such as the aerospace industry, human body implants, the automobile industry, etc.

Directly or indirectly the damage in fretting fatigue is caused by several factors/variables. Several researchers stated [1, 2] that there are around 50 factors that might cause considerable variation in the fretting fatigue behaviour/life. Few notable among them are: normal load, tangential load, relative displacement amplitude, applied bulk load, contact geometry, temperature, frequency, hardness, coefficient of friction, surface conditions etc.

At present, it is generally accepted that some (unknown) convergence of some local parameters is responsible for a reduction in fatigue life.

In order to develop a method that could be useful to estimate the fretting fatigue life a strain based fatigue model has been chosen: the Smith-Watson-Topper model (SWT). This model has been chosen because it includes more intrinsic material properties being then more appropriate to understand either the influence of the material properties as well as to establish a comparison among different materials. The SWT model was already used in the fatigue predictions [3, 4]. In order to obtain a good prediction of fretting fatigue life, as obtained in experimental text, a modification to the SWT model has been proposed in a previous work by the present authors [5]. This modification is related to the effect of the contact damage has on the fatigue life. It has been incorporated into the SWT model a new parameter, called “fretting scar effect” that takes the
form of a stress concentration factor, $K_t$ and it is related to the global shape of the scar geometry. The previous modification affects only the elastic component of the SWT model. It was concluded from the previous work that the predictions seem to be adequate for fretting fatigue life quantifications, depending on the materials.

In order to obtain improved fretting fatigue predictions, the present work proposes a new parameter, the so-called “Bauschinger effect”, which reflects a material deviation from the ideal elastic-plastic behavior. This parameter affects the plastic component of the SWT model. It is expected that BAU parameter may substantially improve the fretting fatigue predictions and the SWT model will become a more universal equation.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

The specimens used for fretting fatigue tests where machined from Al7175 alloy and CK45 steel, and the pads were machined from 34CrNiMo6 steel bars. The choice of different materials for pads and specimen was based on the fact that there are many applications where contact occurs between dissimilar materials, such as the contact between screw/washer and many other components [6] as for example disk/blade attachments in the higher stages of compressor or turbine part of the aircraft jet engines [7]. The mechanical properties of the alloys are given elsewhere [8, 9]. The fatigue cyclic properties of the materials used are given in table 1.

Table 1. Fatigue cyclic properties of the materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cyclic properties</th>
<th>AI7175</th>
<th>CK45</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_f'$</td>
<td>781.74</td>
<td>1319.1</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>-0.1054</td>
<td>-0.1156</td>
<td></td>
</tr>
<tr>
<td>$\dot{e_f}$</td>
<td>0.0689</td>
<td>0.6110</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>-0.5757</td>
<td>-0.5851</td>
<td></td>
</tr>
<tr>
<td>$n'$</td>
<td>0.1617</td>
<td>0.1965</td>
<td></td>
</tr>
<tr>
<td>$K'$</td>
<td>1116.7</td>
<td>1445.5</td>
<td></td>
</tr>
</tbody>
</table>

Symbols in table 1 have the meaning: $\sigma_f'$ - fatigue strength coefficient [MPa]; $b$ - fatigue strength exponent; $\dot{e_f}$ - fatigue ductility coefficient; $c$ - fatigue ductility exponent, $n'$ - cyclic strain hardening exponent; $K'$ - cyclic strength coefficient [MPa].

2.2. Test Specimen for Fretting Fatigue Tests

The fretting fatigue experiments were carried out using the specimen shown in figure 1. It has a special shape with a round cross section and two flat sides (A and B). In this situation two zones of the contact were generated on the flat sides of the specimen.

![Fig. 1. Geometry of the specimen used in fretting fatigue tests.](image1)

2.3. Experimental Setups

Figure 2 shows the fretting fatigue experimental test setup used in this study along with the servo hydraulic uniaxial testing machine. More details about the fretting fatigue setup are given elsewhere [10, 11].

The capacity of the servo hydraulic testing machine is 600 kN under static conditions and 500 kN for fatigue loading. The maximum cyclic loading frequency of the machine is 50 Hz.

The equipment works at ambient temperature, in laboratory environment, but can be also used at low and high temperatures and at other environments.

Figure 3 shows schematically the test configuration in fretting fatigue tests.

![Fig. 2. Fretting fatigue experimental test setup [10, 11].](image2)

![Fig. 3. Schematic specimen-pad contact test configuration: $F_n$ - pad normal load; $F_{tp}$ - pad tangential preload; $F_t$ - pad tangential load; $L_a$ - machine axial load.](image3)
2.4. Experimental Observations

Two series of fretting fatigue tests for each material were carried out at a stress ratio, $R=0.1$, in order to obtain the S-N curves. All tests were conducted at ambient temperature, in a laboratory environment, and at a cyclic frequency of 4 Hz. A summary of the fretting fatigue tests: specimen number, loading conditions and number of cycles to failure are presented in table 2. The fretting fatigue specimens were tested up to rupture.

3. BAUSCHINGER EFFECT – THEORETICAL BACKGROUND

3.1. Initial Remarks

The Bauschinger effect is related to a deviation from the expected plastic behavior of the materials. To the authors’ knowledge, no one has used this effect in fatigue initiation predictions. Only Pommier [12] stated its interest in fatigue crack propagation. She stated that it would change plastic deformed areas both ahead and behind the crack tip affecting the residual stress field ahead of the crack tip but also the closure level behind the crack tip. However its possible effects on fatigue initiation were not discussed up to this work.

Many studies [13-17] have been carried out to understand the BAU effect and technical literature presents several explanations for the BAU effect. The physical origins are generally attributed to (i) internal stresses; (ii) dislocation theories; (iii) composite model (Masing’s model or Asaro’s model).

3.2. Smith-Watson-Topper Model

To predict the fretting fatigue initiation life, it has been chosen the Smith-Watson-Topper model. Here it is presented only the final form of the SWT model. More details are presented elsewhere [5].

\[
\left( \sigma_{\text{max}} + 2p_0 \left( \mu F_{t,max} / F_{n,max} \right) \right) K_f \left( 1 - 2\nu^2 - \nu^3 \right) E
\]

\[
\left( \sigma_a + \sigma_{a,F} \right) = \left( \frac{\sigma_f}{E} \right)^2 \left( 2N_f \right)^{2b} + \sigma_f \left( 2N_f \right)^{b+c}
\]

where: $\sigma_{\text{max}}$ is the maximum machine axial stress; $p_0$ - the maximum Hertzian pressure; $\mu$ - the coefficient of friction in the slip condition; $F_{t,max}$ - the maximum tangential load; $F_{n,max}$ - the maximum normal contact load, $K_f$ - the stress concentration factor; $K_s$ - the surface finishing factor; $\nu$ - the Poisson’s ratio; $E$ - the Young’s modulus; $\sigma_a$ - the machine axial stress amplitude; $\sigma_{a,F}$ - the tangential stress amplitude; $N_f$ - the number of cycles to crack initiation.

3.3. BAU Effect on SWT

In order to incorporate the BAU effect into the SWT model two approaches are presented. It should be mentioned that the SWT model includes several intrinsic properties of the material: fatigue strength coefficient, fatigue strength exponent, fatigue ductility coefficient, fatigue ductility exponent. These properties are obtained from stabilized hysteresis loops (fig. 4). Figure 4 schematically shows a cyclic hysteresis loop and highlighted in red is the BAU effect. It can be seen that when obtaining the previous properties, they do not incorporate or reflect the BAU effect. Thus, the SWT model does not take the BAU effect into consideration.

The first approach is based on energy based models. This is based on the fact that the stored energy in each cycle is reduced due to the Bauschinger effect (figs. 4 and 5). On figure 5 it can be seen the different Bauschinger effect of the two different materials used in the present study. Thus, the fatigue life will be extended.

Figure 6 shows a schematic representation of the BAU energy parameters. The proposed Bauschinger energy parameter is determined as follows:

\[
\beta_{\text{BAU}} = \frac{E_s}{E_p}
\]

where: $E_s$ is the amount of the stored energy and then returned energy, $E_p$ is the plastic prestrain energy.

This first approach proposes the modification of the plastic term of the SWT model, by multiplying the fatigue ductility coefficient by BAU energy parameter.

When the BAU energy parameter is incorporated in the plastic term of the SWT equation, it takes the following form:

\[
\left( \sigma_{\text{max}} + 2p_0 \left( \mu F_{t,max} / F_{n,max} \right) \right) K_f \left( 1 - 2\nu^2 - \nu^3 \right) E
\]

\[
\left( \sigma_a + \sigma_{a,F} \right) = \left( \frac{\sigma_f}{E} \right)^2 \left( 2N_f \right)^{2b} + \sigma_f \beta_{\text{BAU}} \left( 2N_f \right)^{b+c}
\]
### Table 2. Experimental fretting fatigue life results for the material used.

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine axial load, $L_a$ [kN]</th>
<th>Normal pad load, $P_n$ [N]</th>
<th>Tangential pad pre-load, $F_t$ [N]</th>
<th>No. of cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1B1</td>
<td>1200</td>
<td>600</td>
<td></td>
<td>50,342</td>
</tr>
<tr>
<td>A1B2</td>
<td>950</td>
<td></td>
<td></td>
<td>60,897</td>
</tr>
<tr>
<td>A1A5</td>
<td>750</td>
<td>800</td>
<td></td>
<td>50,106</td>
</tr>
<tr>
<td>A1D1</td>
<td>1200</td>
<td>600</td>
<td></td>
<td>82,231</td>
</tr>
<tr>
<td>A1D2</td>
<td>750</td>
<td></td>
<td></td>
<td>77,618</td>
</tr>
<tr>
<td>A1A3</td>
<td>750</td>
<td>800</td>
<td></td>
<td>124,442</td>
</tr>
<tr>
<td>A1A4</td>
<td>750</td>
<td>450</td>
<td></td>
<td>50,707</td>
</tr>
<tr>
<td>A1B5</td>
<td>116,335</td>
<td></td>
<td></td>
<td>116,335</td>
</tr>
<tr>
<td>A1A1</td>
<td>50,231</td>
<td></td>
<td></td>
<td>60,930</td>
</tr>
<tr>
<td>A1A2</td>
<td>54,139</td>
<td></td>
<td></td>
<td>97,933</td>
</tr>
<tr>
<td>A1 9</td>
<td>116,335</td>
<td></td>
<td></td>
<td>76,456</td>
</tr>
<tr>
<td>A1B4</td>
<td>1200</td>
<td>600</td>
<td></td>
<td>123,086</td>
</tr>
<tr>
<td>A1B3</td>
<td>950</td>
<td></td>
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<td>123,086</td>
</tr>
<tr>
<td>AIA6</td>
<td>750</td>
<td>800</td>
<td></td>
<td>66,199</td>
</tr>
<tr>
<td>AIA7</td>
<td>750</td>
<td>600</td>
<td></td>
<td>97,437</td>
</tr>
<tr>
<td>AIA8</td>
<td>450</td>
<td></td>
<td></td>
<td>113,927</td>
</tr>
</tbody>
</table>

The values obtained for the new BAU energy parameter are presented in table 3.

The second approach is based on the theories of internal stresses; dislocation theories; composite model (Masing’s model or Asaro’s model). Internal stresses are widely used to study the BAU effect [13, 14, 16, 17]. Indeed, from a microstructural point of view, the BAU effect has been explained in terms of polarization of work-hardening, due to the accumulation of internal stresses during plastic deformation [13, 14]. The internal stress corresponds to the stress associated with a local strain process leading to long-range interaction with mobile dislocations. From a mechanical point of view, the back stress is associated with the translation of the elastic domain, and thus with kinematic work-hardening [13, 14].

Again, in this case, the BAU effect is incorporated only in the plastic term of both models. In fact, it is modified the value of the fatigue ductility coefficient. From the value of the fatigue ductility coefficient that was determined for the stabilized hysteresis loops, it is subtracted the BAU parameter. It can be seen that when the new fatigue ductility coefficient is incorporated in the models, it will lead to a reduction of fretting fatigue life.

The new fatigue ductility coefficient that incorporated the BAU effect is given by:

$$\varepsilon_{f,BAU} = \varepsilon_f - \varepsilon_{BAU}$$

(4)

where: $\varepsilon_f$ - fatigue ductility coefficient; $\varepsilon_{BAU}$ - BAU parameter.

The proposed BAU parameter is given by:

$$\varepsilon_{BAU} = \ln \left( \frac{100}{100 - \beta_{BAU}} \right)$$

(5)

where: $\beta_{BAU}$ - BAU stress parameter.

When the new fatigue ductility coefficient (with BAU effect) is incorporated in the plastic term of the SWT eq. 1, it takes the following form:

$$\left( \sigma_{\text{max}} + 2\mu P_0 \frac{F_{\text{f, max}}}{F_{\text{a, max}}} \right) \frac{k_f}{k_s} \left( 1 - \frac{t^{2} - t^{3}}{E} \right)$$

$$\left( \sigma_{a} + \sigma_{a, F_f} \right) = \frac{\sigma_f^2}{E} \left( 2N_f^b + \sigma_{f, BAU} \right)$$

(6)

The values obtained for the new fretting fatigue ductility coefficient are presented in table 4.
4. RESULTS AND DISCUSSION

4.1. First Approach – Energy Based Models

Figure 7 shows the analytical fretting fatigue life prediction based on the SWT parameter which takes into consideration the stress concentration factor, $K_t$ and the surface finishing factor, $K_s$ (eq. 1 – dashed blue line). It is also shown the estimated life obtained using the SWT parameter (with $K_t$ and $K_s$ incorporated) affected by the BAU effect (eq. 3 – solid green line).

Table 4. Results of the new fatigue ductility coefficient that incorporates the BAU.

<table>
<thead>
<tr>
<th>Parameter/Material</th>
<th>Al7175</th>
<th>CK45</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon'_{BAU}$</td>
<td>0.0252</td>
<td>0.03119</td>
</tr>
<tr>
<td>$\varepsilon'_{f}$</td>
<td>0.0689</td>
<td>0.6110</td>
</tr>
<tr>
<td>$\varepsilon'_{f,BAU}$</td>
<td>0.0437</td>
<td>0.5798</td>
</tr>
</tbody>
</table>

Table 3. Results of the new BAU energy parameter.

<table>
<thead>
<tr>
<th>Parameter/Material</th>
<th>Al7175</th>
<th>CK45</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{BAU}$</td>
<td>2.49</td>
<td>3.07</td>
</tr>
</tbody>
</table>

Fig. 7. Maximum axial stress ($\sigma_{max}$) vs. number of cycles (SWT – $K_t$, $K_s$ and BAU energy).

Fig. 6. Schematic representation of the BAU effect parameters [13] ($\sigma_{max}$ - the pre-stress reached during the first loading, $Re_2$ the reverse loading yield stress, $\beta$ - the stress shift between the two work hardening curves, $E_s$ – the ratio of the amount of stored and then returned energy, $E_p$ - the plastic pre-strain energy, $\varepsilon_{p,\max}$ - the plastic pre-strain).

Fig. 5. Cyclic Hysteresis Behaviour: a) Al7175; b) CK45; $\sigma_{max}$ - maximum stress; $\sigma'_y$ – yield stress; $\sigma'_y$ – reverse yield stress [18]
The main aspect to be highlighted is that the BAU effect introduced in the SWT parameter has a very small effect on fretting fatigue life in the case of Al7175 alloy (fig. 7a - solid green line), that is neither beneficial nor detrimental.

From figure 7b (solid green line) it can be seen that the BAU effect in the case of CK45 steel has a significant effect on fretting fatigue life. The predicted results in the case of CK45 steel are much closer to the experimental results when the BAU effect was introduced into the model.

4.2. Second Approach – Internal Stresses, Dislocation Theories

Figure 8 shows the analytical fretting fatigue life prediction based on the SWT parameter which takes into consideration the stress concentration factor, $k_t$, and the surface finishing factor, $k_s$ (eq. 1 – dashed blue line). It is also shown the estimated life obtained using the SWT parameter (with $k_t$ and $k_s$ incorporated) affected by the BAU effect (eq. 6 – solid green line).

From figure 8a (solid green line), it can be seen that in the case of Al7175 alloy the BAU effect did not have any influence on fretting fatigue life. In the case of CK45 steel (fig. 7b – solid green line) when the BAU effect was incorporated in the SWT parameter it had a significant influence on fretting fatigue life. This correction is leading to a worse prediction in the case of CK45 steel.

It should be mentioned that by incorporating the BAU effect into the SWT model, it can be seen that it does not have any influence on the materials that have a very small BAU effect (Al7175 alloy) but improved the life of the materials that have a significant BAU effect (CK45 steel). It can be concluded that now the SWT model used in this study becomes a more universal (general) equation.

Regarding the two BAU approaches presented in this work, energy based and internal stresses/dislocation theories, is the opinion of the author of this work that the one that should prevail is the energy based approach. The reason lies on the fact that makes more sense, physically speaking, that the reduction in the energy consumption per cycle would increase the fatigue life. Furthermore, the explanation, as presented by Pommier [12, 15, 19], which caused an increase in damage due to the BAU effect, is based on physical aspects (residual stresses and crack closure) either ahead and behind the crack tip. It was not defined which (ahead or behind) was the most relevant. Pommier demonstrated that it is relevant on crack propagation (because there a crack exists) but not on crack initiation (no existing crack – no crack closure).

5. CONCLUSIONS

The main conclusion of this research can be drawn as follows:

- The BAU effect, as proposed in this work, has a substantial influence on life predictions, when an energy based approach is used. A significant BAU effect takes place in CK45 steel while the BAU effect has a very small influence in Al7175 alloy.
- By incorporating the BAU effect into the SWT model, it can be seen that it does not have any influence on the materials that have a very small BAU effect but improved the life of the materials that have a significant BAU effect.
- Finally it can be concluded that the model used in this study (SWT) becomes a more universal (general) equation if the BAU effect is incorporated.

ACKNOWLEDGEMENT

The research presented here was carried out in the Materials Testing Laboratory of the Mechanical Engineering Department of University of Minho, and was supported by “Fundação para a Ciência e a Tecnologia” (Portugal) through the PhD grant with the reference SFRH / BD / 19555 / 2004.
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