Estimation of the duration life in thermomechanical fatigue using finite element post-processing

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Abstract

In this study lifetime of structural parts subjected to thermomechanical fatigue, occurring under concurrent thermal and mechanical cycles is assessed. The special effect of phasing between thermal cycles and strain cycles was analysed. The methodology used was based on finite element post-processing analysis by specialized fatigue software package. A parametric study conducted on a standard specimen under various conditions of loadings had shown that thermomechanical fatigue is a complex phenomenon. In particular, it is not always more damaging than isothermal fatigue as usually believed.

1. Introduction

Thermomechanical fatigue (TMF) occurs in specific structures such as turbine blades and motor components as they are exposed to high combustion temperatures and high vibratory and friction loads. Material properties such as tensile strength, yield strength and Young’s modulus decrease in general with increasing temperature. Fatigue lifetime properties are also temperature dependent. High temperature fatigue conditions imply that the fatigue load and temperature vary both as a function of time. As a result, fatigue damage accumulation is modified with increasing temperature. If thermal expansion is restricted, then thermal stresses are induced and fatigue will be affected also by structural aspect such as the actual boundary conditions. In addition to the cyclic strain, time and temperature are two more variables. The combined action of cyclic strains at high temperatures with time-dependent temperature variations constitutes the mean features of what it is called thermomechanical fatigue. The complexity of this problem scenario in practice is recognized to be considerable.

Thomas et al.,[1] had shown through experiments that TMF testing is more severe that isothermal testing conducted at the maximum temperature. Fatigue damage is dependent on the phase relationship between strain and temperature. Bill et al.,[2] had found that lifetime of material specimens under in-phase (IP) thermomechanical cycling is well below isothermal fatigue lives obtained for a number of temperatures belonging to the temperature ranges that were investigated. Phase effects in the special case of metal matrix composites undergoing low cycle fatigue were discussed in [3].

There are two extreme thermomechanical situations; (IP) and out-of-phase (OP) cycles. Under IP cyclic loading, the maximum strain occurs at the same time as the peak temperature, and the minimum strain occurs at the minimum temperature. Under OP cycles, the maximum strain occurs at the minimum temperature, and minimum strain at the peak temperature. In many works reported in the literature, both in-phase and out-of-phase stress and temperatures cycles were found to be more damaging than isothermal stress cycles. Often, but not at all times, in-phase stress and temperature cycles were found to be more severe than out-of-phase cycles.

Models for the prediction of TMF lifetime are essential in order to anticipate when to change the fatigue sensitive components. Predicting lifetime can increase reliability and reduce serviceability costs. A large number of thermomechanical fatigue models were proposed in the literature, [4]. They
can be classified into damage summation, strain-range partitioning, and strain energy partitioning. Each model was derived for particular use of a given material under specific ranges of temperature and cyclic strain. No versatile model could yet be used to predict in all circumstances lifetime under arbitrary thermomechanical loading.

In this work, TMF is analysed under various combinations of strain and temperature cycles by considering both IP and OP cycling. Finite element modelling of a standard test specimen is performed. Considering the Coffin-Manson fatigue model, the specialized fatigue post-processing software package, fe-safe, was used to assess lifetime as function of the considered TMF loading.

2. Lifetime modelling in TMF

Different approaches have been introduced for the prediction of TMF lifetime, [6,7]. Rough phenomenological models relate measured total mechanical fields and lifetime without considering explicitly the different physical damaging mechanisms. Other approaches are cumulative damage based models where explicit consideration of the different damaging mechanisms is carried out. There are finally crack growth based models for which life is related to local inelastic strain at the crack tip. Gocmez et al. [7] have reviewed the classical fatigue criteria that were initially introduced for the uniaxial isothermal case. Since in reality engineering components are likely to experience multiaxial anisothermal loading, these early models had been extended subsequently. The concept of critical plane was introduced to incorporate isothermal multiaxial loading. Its extension to anisothermal loading needs yet to be achieved by taking into account temperature dependency of material parameters.

Energetic criterions based on energetic approaches showing a relation between dissipated energy and the number of cycles to failure were introduced by [8,9]. Gocmez et al.,[7] has extended this approach to take into account mean stress effect. However the application was focused on predicting life under uniaxial low cycle fatigue under OP-TMF. The generalization to multiaxial case is yet to be achieved. From a practical engineering point of view, strain range partitioning based methods are more adequate. In these empiric approaches damage mechanisms are considered separately, [3,10]. The needed model parameters are to be identified from specific tests.In this work, the strain-life curves for isothermal fatigue analysis are defined under the following form
\[
\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E} \left(2N_f\right)^b + \frac{\epsilon'_f}{\left(2N_f\right)^c}
\]
(1)

Where \(E\) is the Young's modulus, \(\sigma'_f\) is the fatigue strength coefficient, \(\epsilon'_f\) the fatigue ductility coefficient, \(b\) the Basquin’s fatigue strength exponent and \(c\) the Coffin-Manson fatigue ductility exponent.

To take into account TMF with varying phase relationship between temperature and strain cycles, parameters \(c\) and \(\epsilon'_f\) are changed in the low cycle fatigue section of the strain-life curve according to the post-processing fatigue software, (Fe-safe, 2008). The modification is defined in terms of two thermal factors which are specific to a material: one for in-phase cycling and the second for out-of phase cycling. This is performed according to the modified life equation
\[
\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E} \left(2N_f\right)^b + \frac{\epsilon'_f}{\left(1-\psi_1\right)^c\left(2N_f\right)}
\]
(2)

With \(\psi_1 = (1 - tf_{\text{lin}})\cos(\varphi)\) and \(\psi_2 = (1 - tf_{\text{out}})\sin(\varphi)\), where \(\varphi\) is the phase angle between the strain and temperature cycles. If \(tf_{\text{lin}} = 1\) and \(tf_{\text{out}} = 0\), then the isothermal damage curve would be retrieved. These two factors would normally be derived from plastic strain component of the
strain-life curve. For each fatigue cycle, the actual phase relationship between strain and temperature is used to adjust the strain-life curve for any part of the analysed structure.

3. Numerical modelling of TMF

The specimen used in the numerical modelling is the standard CT16 specimen, figure 1. This specimen may be modelled in 2-D plane with a thickness B = 16 mm, equal to the net thickness of the 3-D specimen. The other dimensions are the CT specimen width W = 32 mm and the initial crack length a = 0.25W. P designates the applied pressure on the outwards halves of the holes (Pa).

To obtain thermal stresses that do not vanish under uniform temperature field the specimen was fixed against horizontal displacement along the boundary zone 1 and against vertical displacement along the boundary zone 2. Thermal cycles are then considered to act simultaneously with elastic or elastic plastic strain cycles that are applied on the CT16 specimen. The material properties used are those of the stainless austenitic steel 316 L. Abaqus software is used to develop the finite element numerical model representing the test sample CT16 under the plane stress assumption. Mesh refinement is a crucial issue in the finite element simulation of fatigue. Abaqus option on adaptive remeshing integrating both energy and strain criteria were used.

The stress-strain curves for the thermomecanical fatigue of steel 316 L are defined in terms of the Young’s modulus E, the strain hardening coefficient $K$ and the strain hardening exponent $n$, as

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}}$$

(3)

This steel was tested in the temperature range 20°C-700°C. Denoting $\nu$ the Poisson’s coefficient, $\sigma_0$ the yield stress and $\sigma_m$ the ultimate strength, tension data of 316L steel are summarized in table 1.

Figure 2 presents the temperature dependent plastic curves of this material for the three temperatures: 20°C, 500°C and 700°C; plastic behaviour is shown to depend slightly on temperature. The thermomecanical loading was selected according to either the in-phase mode between pressure P and temperature T, or to the out-of-phase mode between these two quantities. Three different types of analyses were performed under Abaqus software: one cycle isothermal mechanical loading; one cycle IP-TMF loading; and one cycle OP-TMF loading.

Abaqus finite element results are transferred as inputs to fatigue post-processing software, [5]. Use is made here of the additional module TMF for thermomechanical fatigue solution. User can define load cycles to be analysed through many implemented mathematical functions and block operations. F-safe interpolates linearly the yield stress, the ultimate tensile stress and the endurance limit. Beyond the extremes of temperature interval the values at these extreme temperatures are used respectively.
For a TMF analysis, a minimum of 4 sets of data should be defined corresponding to at least 2 different temperatures and two different strain rates. Table 2 summarizes fatigue data for 316L steel. The TMF module allows converting isothermal fatigue life to an in-phase thermal cycle (0°) and an out-of-phase thermal cycle (180°C) in order to use the lifetime curve as defined by equation (2).

### Table 1. Tension data for the 316 L steel in temperature range 20 °C - 700°C.

| Temperature | E (MPa) | ν | σ₀ (MPA) | σₘ (MPa) |
|-------------|---------|---|----------|----------|
| 20 °C       | 193468  | 0.33 | 245.63   | 500      |
| 500 °C      | 152754  | 0.33 | 192.19   | 460      |
| 700 °C      | 142304  | 0.33 | 178.53   | 367      |

### Table 2. Fatigue data for the 316 L steel in the temperature range 20 °C- 700 °C.

| Temperature | K (MPa) | n   | b     | C    | \( E_f' \) (MPa) | \( \sigma_f' \) (MPa) | S value for \( N_f = 10^4 \) | S value for \( N_f = 10^6 \) |
|-------------|---------|-----|-------|------|------------------|------------------|-------------------|-------------------|
| 20°C        | 763.3   | 0.157 | -0.0835 | -0.5142 | 0.476           | 703.4           | 307.7             | 209.4             |
| 500 °C      | 848.41  | 0.206 | -0.0903 | -0.414 | 0.1272          | 582.6           | 238.2             | 157.2             |
| 700 °C      | 729.2   | 0.1954 | -0.084 | -0.4281 | 0.0821          | 848.42          | 195.2             | 138.6             |

### 4. Results and discussion

A parametric study is conducted on the CT16 specimen having the material data specified in section 3 under the following conditions: The applied pressure in Pa is varied in the set \{ 9×10^6 ; 1.3×10^7 ; 1.5×10^7 ; 1.7×10^7 \}, the reference temperature in °C is varied in the set \{200, 500\}, the temperature gradient in °C takes one of the two values\{5, 10\}.

Figure 3.a gives, at the reference temperature 200°C, the obtained results in terms of lifetime cycles for all the TMF loadings. Figure 3.b gives, in the same conditions as for figure 3.a, lifetime cycles but with the reference temperature equal to 500°C. Unlike what is largely known from literature dealing with TMF, figures 3.a and 3.b show that the isothermal loading is more damaging in some cases than the thermomechanical loading.

A net distinction appears between elastic plastic regime\{1.3×10^7 ; 1.5×10^7 ; 1.7×10^7 \} and the elastic regime 9×10^6 Pa. One can notice that an elastic regime is recovered also with 1.3×10^7 Pa and \( \Delta T = 10°C \) for the OP case. On the opposite, an elastic plastic regime was recovered with 6×10^6 Pa and \( \Delta T = 10°C \) for the IP case. In the presence of plastic strains, only small differences appear between the isothermal, the in-phase and out-of-phase cycling. In some occasions the IP loading is more damaging, while in other cases the OP loading is more severe. This can also be verified when considering the thermomechanical loading for which only elastic strains occur, 6×10^6 Pa.
Life for TMF loadings as function of the applied mechanical load and thermal gradient;

5. Conclusions
Lifetime of the CT16 specimen with special boundary conditions and which was subjected to the action of various thermomechanical loadings was investigated by using finite element numerical modelling followed by fatigue pos-processing. Numerical simulations have shown that thermomechanical fatigue is not always more damaging than isothermal fatigue. Furthermore, no general conclusions could be drawn as to the relative influence of the in-phase cycles in comparison with the out-of-phase cycles. Under plastic strains, only small differences appear between in-phase cycles and out-of-phase cycles. Considering both elastic and elastic-plastic regimes, comparison between these two scenarios has revealed that the out-phase mode can be more severe, but also less severe than the in-phase mode.

6. References
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