Fatigue Analysis of a Piston with ABAQUS and a Thermo Mechanical Method According Sehitoglu

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Abstract:

The fatigue life of power train components can be improved dramatically by finding crack initiation points with suitable software tools and optimization of the critical areas. With increasing capacities of computers the prediction of the fatigue life for components by numerical methods gets more and more important. The modern virtual development process is able to include many physical effects to enable realistic analyses.

Due to high engine operating temperatures, thermo mechanical fatigue during start – stop cycles of the engine is a very important design consideration. Strains rates, temperature and phasing effects between temperatures and stresses within the piston have to be considered. These results are obtained conducting a sequentially combined thermo mechanical analysis with the software ABAQUS. Transient temperature distributions are first determined for a time-dependant oil temperature. The time-dependant temperature results are then introduced in a mechanical analysis where the material is defined as elastic plastic and temperature dependent. Making use of the finite element results, the Sehitoglu's fatigue life method allows predicting the thermo mechanical low cycle fatigue of the piston. The fatigue life post processor (FEMFAT) computes the local damages using specific TMF material parameters. This method takes into account the specific damages due to the mechanical loading, the oxidation process and the creep.

The presentation deals with an application on a piston of the software ABAQUS and the Sehitoglu's TMF method to access the thermo mechanical fatigue life due to transient temperature distributions.
The theoretical background and the computational assessment of TMF loaded structures will be presented. The practical application on a piston structure will be shown.

Keywords:

ABAQUS, Sehitoglu, TMF, Damage, Life, Low cycle fatigue, Piston, Automotive Structures

Simulation procedure

The aim of the piston study is to predict the initiation of cracks due to the start/stop thermal cycling of the engine. The procedure described here makes use of the software ABAQUS to produce the necessary temperature, stress, strain distributions required to carry out thermo mechanical durability calculations based on the Sehitoglu's method (used software FEMFAT). The ABAQUS - results together with the corresponding TMF- material parameters are then processed to access the lifetime of the part. The different steps carried out for the simulation are shown in figure 1.

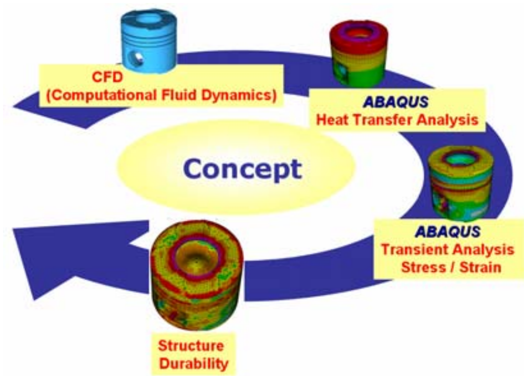

Figure 1: Simulation procedure

FE – Simulation with ABAQUS

The FE – analyses with the commercial software ABAQUS consist of a sequentially combined thermal-stress analysis. A transient heat transfer simulation is conducted to generate the temperature distributions of the piston for different operating points of the engine. This step is followed by a mechanical simulation, in which the previously obtained temperature distributions are applied. The corresponding stress, strain, deformation are

simulated.

Figure 2 shows the evolution of the engine rpm as a function of the time and the corresponding oil temperatures.

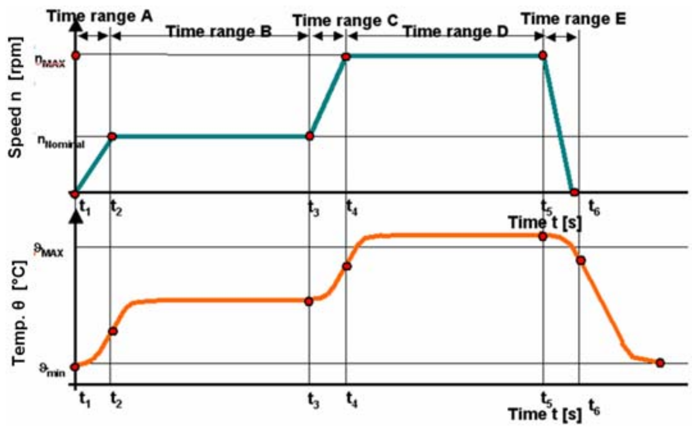

Figure 2: Evolution of the imposed rotational speed and the oil temperature

A convection condition is defined at the gas side successively for oil temperatures corresponding to the different working points. The thermal cycle is made up of 3 phases during each 60 seconds: warm up from room temperature to idle, warm up from idle to the maximum temperature, cooling down back to room temperature. The oil temperature which constitutes the only time-varying variable in this study is maintained constant at temperatures of respectively 110, 150 and 20° Celsius between the different working points. Temperature distributions are simulated using time increments of 3 seconds i.e. 20 increments between the working points. Convection temperatures defined as shown in figure 3 with film coefficient of 1.

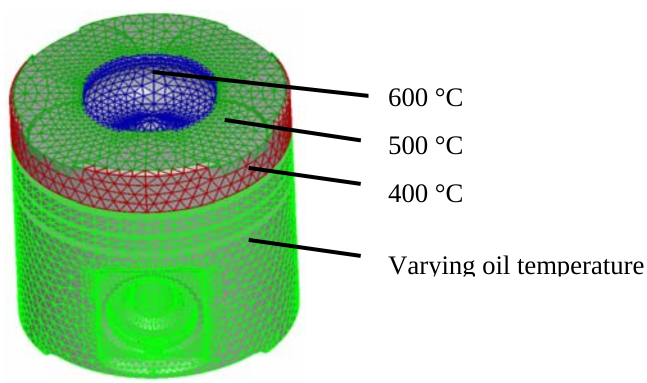

Figure 3: Applied convection temperatures

The material of the piston is an aluminum alloy with silicon. Conductivities of the piston as well as of the pin material are defined as temperature dependant.

Figure 4 here below presents the evolution of the temperature distribution at different time points: start at room with oil at room temperature, end of the warm up phase, end of the maximum loading phase, end of the cooling down.

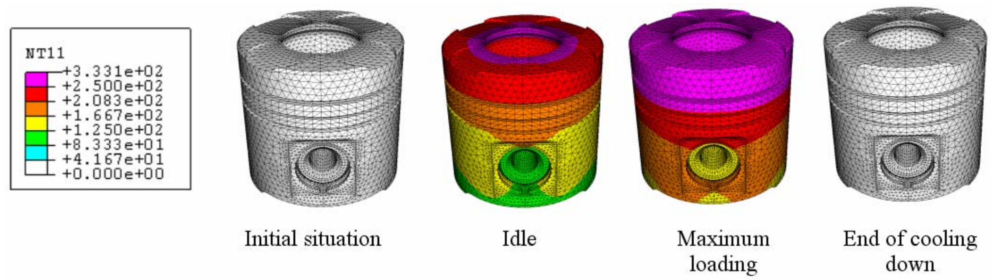

Figure 4: Evolution of the temperature distributions for the different working phases

The temperature distributions are applied in the mechanical analyzes to determine the thermal strains for every time increment calculated in the thermal transient analyze. The pressure produced at the ignition is shown in figure 5. The boundary conditions are defined by the constant pressure loading at the combustion chamber side of the piston and the clamping of the piston pin at the con rod connection.

A non-linear analysis is conducted considering:

- Contact between the pin and the piston,
- Non-linear geometry,
- Isotropic plasticity model,
- Temperature-dependant material properties: stress-strain curves, thermal expansion, and conductivity.

The material law used in this example is issued from a monotonic traction experiment and one warm up – cooling down loop is simulated with ABAQUS. Creep phenomena are not taken into account in the ABAQUS material definition.

To optimize the calculation time the mechanical simulation is realized at each time increment in two steps with the corresponding temperature distribution. A unitary combustion pressure is first used to close the contact between the piston and the pin. In a second step, the full combustion pressure of is then applied.

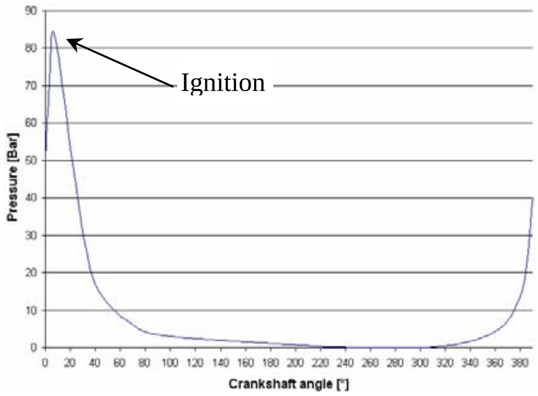

Figure 5: Pressure in cylinder as a function of crankshaft

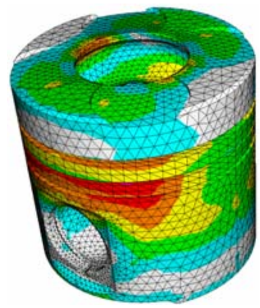

Figure 6: Mises stress distribution at the end of the phase where the maximum oil temperature is applied

As for the temperature distributions, 20 stresses states of the piston are simulated for every time increment during the different working phases. The figure 6 shows the Mises stress distribution for the maximum oil temperature.

The low cycle fatigue analysis with the Sehitoglu's method (using the commercial fatigue software FEMFAT) requires for every time step ABAQUS outputs for transient stresses, transient strains (total strain), and transient temperatures. The time information used in fatigue life post-processing can be provided directly by ABAQUS or by a separate table. Both Fil-format file and Odb-format file format can be used as input for the fatigue life simulation. The required ABAQUS output are requested using the following commands:

```
*NODE FILE, FREQUENCY=1, GLOBAL=YES
NT,U
*EL FILE, FREQUENCY=1, DIRECTIONS=YES, POSITION=NODES
E,S
*OUTPUT, FIELD, FREQUENCY=1
*ELEMENT OUTPUT, VARIABLE=PRESELECT, POSITION=NODES
E,PEEQ,S
*NODE OUTPUT
NT,U
```

Low cycle fatigue predictions with Sehitoglu's theory

The Sehitoglu's method allows accessing the low cycle thermo mechanical fatigue life taking into account the phase lag between loading and temperature, the stresses, the strain amplitudes and the strains rates within the considered structure. Applications for TMF- LCF are concentrated on the following engine construction components: Cylinder head – exhaust manifold – piston – turbocharger (hot side).

In accordance to Sehitoglu's hypothesis the total damage of thermo-mechanical stressed components is given by the sum of the mechanical damage, the damage from elevated temperature at environment (oxidation) and the damage from creep processes [2].

Mechanical damage is estimated using the Coffin-Manson equation.

$$\frac{\Delta\varepsilon_{mech}}{2} = \frac{\Delta\varepsilon_{mech}^{e}}{2} + \frac{\Delta\varepsilon_{mech}^{pl}}{2} = \frac{\sigma'_f}{E}\left(2N^{fat}\right)^b + \varepsilon'_f\left(2N^{fat}\right)^c \quad (1)$$

The constants $\left(E, \sigma'_f, b, \varepsilon'_f, c\right)$ are determined from isothermal room-temperature fatigue tests. The mechanical strain used in this equation represents the difference between the total strain and the thermal strain.

What is known as oxidation damage is explained by the successive rupture and re-growth of oxide layers into the material.

The oxidation damage is calculated using following equation:

$$D^{ox} = \frac{1}{N^{ox}} = \left[\frac{h_{cr}\delta_0}{B\Phi^{ox}K_p^{eff}}\right]^{-1/\beta} \frac{2\left(\Delta\varepsilon_{mech}\right)^{(2/\beta+1)}}{\dot{\varepsilon}_{mech}^{(1-\alpha/\beta)}} \quad (2)$$

where h_{cr}, δ_0, α, β and B are material parameters. $\dot{\varepsilon}_{mech}$ is the mechanical strain rate and K_p^{eff} is the effective oxidation constant.

For oxidation damage the influence of the strain rate, the temperature and the phase between thermal and mechanical stressing are taken into consideration. Oxidation damage reaches a maximum for completely clamped out-of-phase (OP) loading (see Figure 7). For materials without surface oxidation, this term can be interpreted as material deterioration from elevated temperature [4].

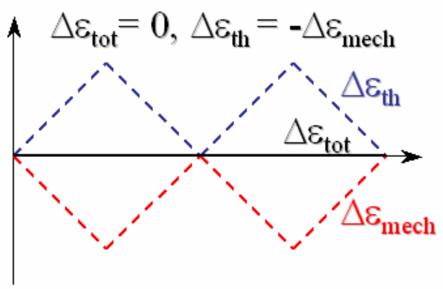

Figure 7: Out of phase loading (OP)

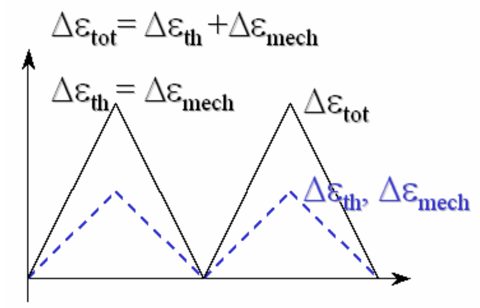

Figure 8: In phase loading (IP)

Creep damage is caused by mechanisms such as void growth and cracking along grain boundaries.
The creep damage is calculated using following equation:

$$D^{creep} = A\Phi^{creep} \int_0^{t_C} \exp\left(\frac{-\Delta H}{\mathrm{R}T(t)}\right)\left(\frac{\alpha_1 \sigma_{eq} + \alpha_2 \sigma_H}{K}\right)^m dt \quad (3)$$

where σ_{eq} is the equivalent stress, σ_H is the hydrostatic stress, K is the drag stress, Φ^{creep} is the creep phasing factor, A and m are material constants, and α_1 and α_2 are scaling factors.

Time-dependent stresses are employed for creep damage and the influence of temperature level and the strain rate are taken into consideration. According to Sehitoglu, creep damage is maximal for in-phase (IP) loading condition (see Figure 8).

Different material parameters in accordance with the Sehitoglu's theory are required for each damaging process (mechanical, oxidation, creep). These parameters are obtained in two steps. In a first step, some specific material experiments are conducted. These experiments are dedicated to the 3 damaging processes.

- Mechanical damage: isothermal strain – life curve at room temperature
- Oxidation damage: isothermal strain – life curve at higher temperatures and high strain rates (to avoid creep effects), out-of-phase thermo mechanical fatigue test and its corresponding temperature/stress/strain history.
- Creep damage: isothermal strain –life curve at higher temperatures and at low strain rates (to take creep effects into account).

In a second step, parameters sets that fit the best the experimental results are determined using evolution algorithms (implemented in Maple language).

The FE-results i.e. stresses, strains, strain rates, temperature distributions together with the Sehitoglu's material parameters enable the calculation of the damage for one start/stop cycle of the engine. Figure 9 illustrates the results of the damaging processes.

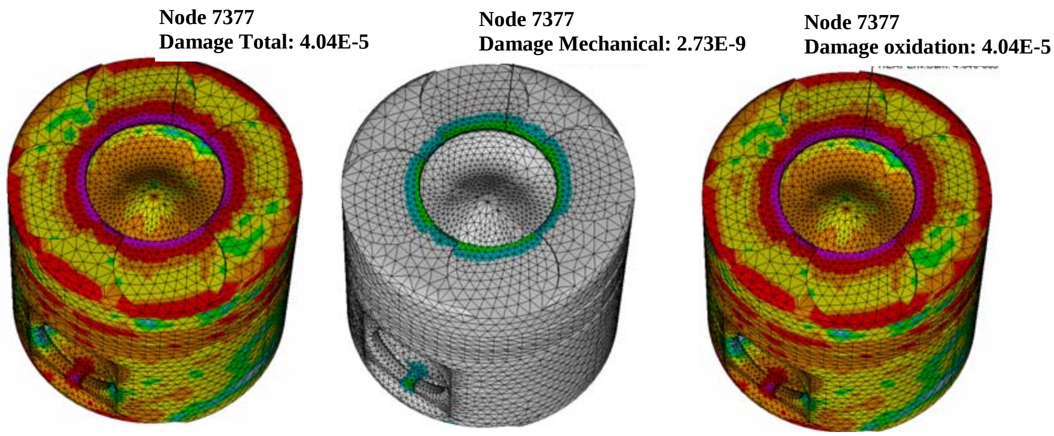

Figure 9: TMF loaded piston

The highest damages take place at the "Muldenwand" piston crown. Due to high temperature variations and compressive stresses at this location, the out-of-phase loading and the corresponding oxidation damage is preponderant. The creep damage is negligible in this case.

Conclusion

This paper presents a methodology to access effectively fatigue life of a component under thermo mechanical loading in the low cycle fatigue domain. The thermal transient and mechanical simulation ABAQUS allows to calculate the different fields (temperature, stress, strain, strain rate) required for the fatigue life post-processing using the Sehitoglu's theory. This study demonstrates the feasibility of accessing the effects of both mechanical and thermal loadings at an early stage of the development. Obtaining and implementing satisfying material parameters and laws constitutes still a crucial point for both finite element and fatigue life simulations.

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