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Low cycle fatigue of alloys in hot section components: progress in life assessment

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Abstract

Hot section components are exposed to high temperature operation and thermal transients during service life. The research of improved performances leads to consider the risk of crack initiation due to isothermal (LCF) or thermal-mechanical (TMF) low cycle fatigue loading in component design. This article gives a short survey of progress in LCF and TMF life estimation procedures due to the description of metallic alloys behavior (superalloys, cast iron, stainless steels). Assessing the lifetime under cyclic loading conditions requires constitutive models accounting for viscoplasticity at service temperatures or during transients. These models can be validated at the laboratory scale using thermal mechanical fatigue tests. Crack initiation life prediction models can be quite simple or need to account for creep-fatigue interactions or environmental effects. Examples illustrate advances in materials studies and models over the years in aero-engine and automotive applications.

Keywords: low-cycle fatigue, thermal-mechanical fatigue, superalloys, cast iron, stainless steels, constitutive equations, damage models

1. Introduction

Low Cycle Fatigue of alloys in hot section components occurs in many industrial applications, especially in aero-engines in jet and aircraft, in aerospace, in powertrain in the automotive industry and in power plants. The design of components experiencing thermal transients and high temperature operation was only at an early stage in the 1980's. Isothermal low cycle fatigue (LCF) tests on specimens were mostly used since Coffin-Manson law

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shows the importance of small plastic cyclic strains. On the other hand thermal shock (TS) tests on simple structures were used to simulate more closely the effect of temperature cycles on material behavior (Glenny 1959-1960, 1967) but their quantitative analysis requires thermal and mechanical stress analysis as for real components (Spera 1969). At that time finite element (FE) analyses were mostly thermo-elastic and plasticity was estimated using drastic approximations. Major progress occurs since 1990 with the development of non-linear finite element models and continuous increase in computer capabilities, the use of constitutive models for cyclic plasticity and visco-plasticity (Chaboche 1991), and the development of reliable thermal mechanical fatigue (TMF) tests (Taira 1973, Hopkins 1976) combining electro-mechanical or servo-hydraulic machines and personal computers. TMF can be used to test independently constitutive models and damage models under thermal transients (Malpertu 1990, Koster 1994, Rémy 2003, Szmytka 2013 b) while the TS tests enable to validate the whole design chain to estimate the component lifetime (Rezai 1988 a and b, Koster 1996). A review of the subject was made earlier (Rémy 2003).

This article gives a short survey of design-oriented materials research with PSA and Ecole Polytechnique, and Safran Aircraft Engines using a few examples. This encompasses testing and constitutive equations with the assessment of TMF of cast iron exhaust manifolds, short crack growth tests in powder metallurgy (PM) superalloys and defect tolerance for turbine discs in aero-engines, high temperature LCF and TMF life prediction of single crystals for high pressure turbine blades and a multi-scale approach for welded parts exposed to TMF. Only enriched engineering models are considered here, compromising between cost effectiveness and complexity of physical mechanisms.

2. Results and discussion

2.1. Testing and constitutive equations: TMF of exhaust manifolds

Building cars that consume less and that minimize environmental impact lead to an increase in temperature and thus visco-plasticity of alloys. Thus design of components such as manifolds or cylinder heads needs accurate constitutive models. The first step is to generate an extensive database using laboratory tests at various temperatures corresponding to the operation range, and covering a large range of strain rates. Cyclic stress-strain tests were conducted under strain control using an incremental testing procedure with 10 to 20 cycles at a given strain amplitude including a strain hold at maximum strain to identify stress relaxation curves. The stress relaxation curves give access to the visco-plastic multiplier. In particular it was shown for SiMo cast iron (Szmytka 2010) that Norton's law that is widely used by most authors (Chaboche 1991) does not give a very good description of relaxation data. A much better result was achieved using an exponential or hyperbolic sine law (Szmytka 2010).

A new constitutive model was thus proposed inspired by dislocation theory based on the Orowan equation relating shear strain rate to dislocation density and the theory of thermally activated glide. This was previously used in creep models for superalloys (Chateau 2010). Further improvement of these models is reported elsewhere (Rémy 2013 a). Validation of the model was obtained using TMF tests under out-of-phase compression strain loading conditions derived from the thermal analysis of components.

A good agreement was observed between model and TMF experiment for conditions corresponding in most places of the structures and to critical zones (Fig.1 a, b). The model was identified using the Z-set code and then implemented as an Umat in Abacus (Szmytka 2013 a). The standard procedure at PSA is to use maximum dissipated plastic strain energy density as criterion to crack initiation under TMF conditions (Charkaluk 2000). The location of crack initiation was properly predicted as the lifetime around 3200 cycles for 3000 cycles in component bench tests. Further the manifold displacements corresponding to leak risks were correctly predicted, that involves ratcheting (Szmytka 2010, 2013 a), which is more demanding for models.

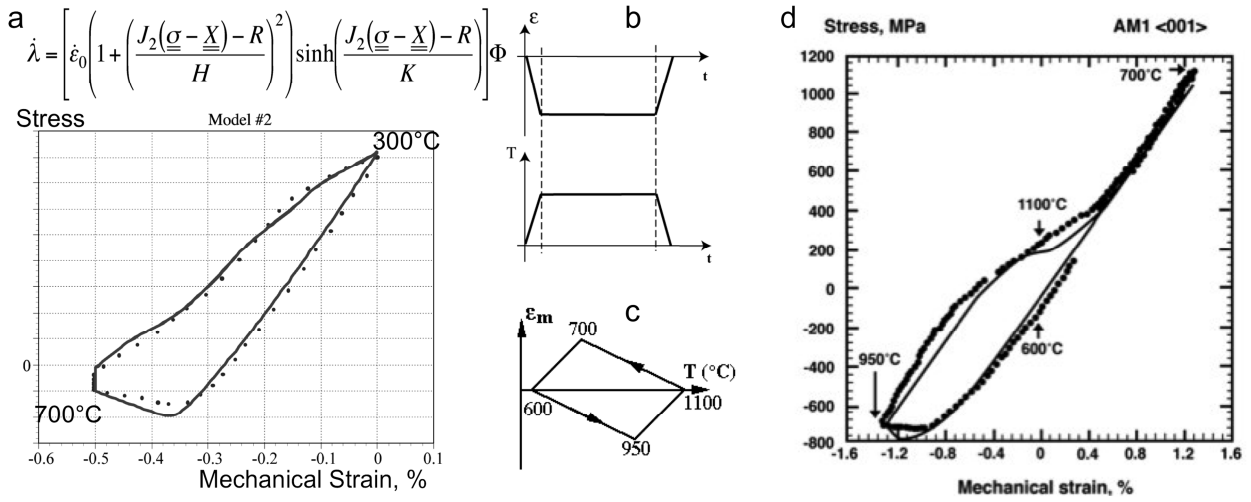

Fig. 1. Comparison between model and experimental TMF stress-strain loops: (a) visco-plastic multiplier and loop for cast iron using the loading cycle shown in (b); (b) out-of-phase cycle with hold time in compression strain; (c) diamond type strain-temperature TMF cycle for blade; (d) comparison between model and experiment for AM1 single crystal using TMF cycle shown in (c).

2.2. Defect tolerance in PM superalloy for turbine discs in aero-engines

The constant research for temperature and performance increase in aircraft engines lead to increase the volume fraction of strengthening precipitates in nickel base superalloys. Wrought alloys can no longer be used when this fraction reach levels around 40 or 50 volume percents. Components have to be made using powder metallurgy and molten metal atomization. The powder is sieved to eliminate the largest ceramic inclusions coming from processing. However in specimen and component tests, LCF cracks initiate mostly at ceramic inclusions. Relevant specimen testing becomes a problem since process defects are very rare. A large scatter is observed in standard LCF tests. Therefore standard design procedures using a given level of risk such as one failure per one thousand tests are no longer practicable. Specimen failure surface analysis shows the larger the inclusion size, the shorter the life (Lautridou 1990). Surface defects are more detrimental presumably due to oxidation effects. Since the inclusions are scarce, there is a volume effect between specimen and component. The occurrence of inclusions in a volume V can be described as the following equation:

$$P(D > D_0) = 1 - \exp(-N_v(D > D_0) \cdot V) \tag{1}$$

And a probabilistic model should be used to assess LCF life (de Bussac 1993). A database and short fatigue crack growth rate (FCGR) data based on Linear Elastic Fracture Mechanics (LEFM) are used to validate methodology. The assumption that a defect can be considered as a crack of the same area is used (Murakami 1994).

FCGR data for long cracks and artificial short cracks (using single edge notch specimen with crack size shorter than 0.1mm) were produced in air and under vacuum (Grison 1997). Vacuum was assumed to be representative of conditions prevailing at inclusions cracking in bulk of material. While in air a fatigue threshold was observed due to oxide wedge closure effects, under vacuum there is a transition in rates with propagation at very low rates associated with crystallographic crack growth. A database has been generated using specimens that were enriched on purpose with inclusions to ensure a satisfying occurrence of crack initiation at defects (Lautridou 1990). A deterministic fatigue life was estimated using the location and size of initiating inclusions and the LEFM data of short fatigue cracks.

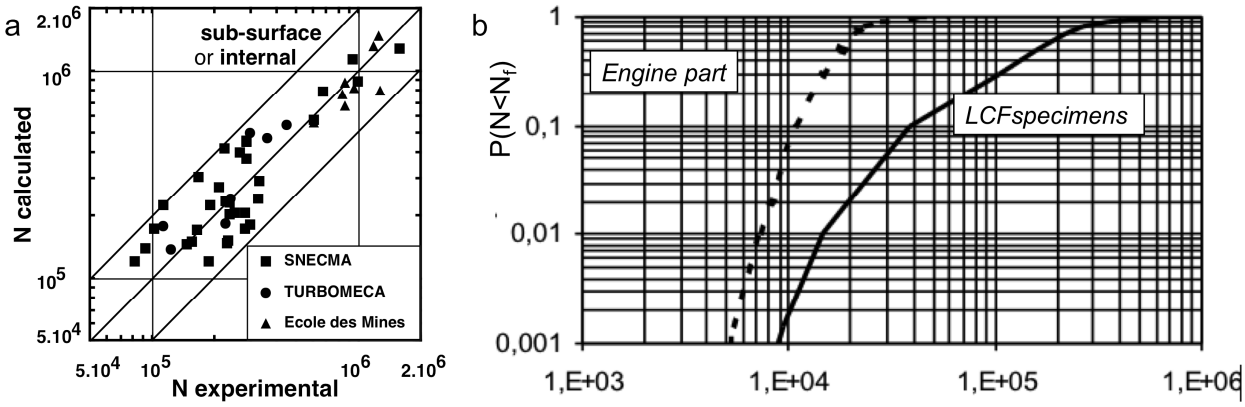

Fig. 2. (a) Comparison between computation and experiment for sub-surface or internal inclusions using short crack data under vacuum; (b) predicted probability of failure for engine part and LCF specimens as a function of fatigue life.

A pretty good agreement was obtained from the integration of da-dN versus ΔK curves for surface initiation using air data and internal or subsurface inclusions using vacuum data (Fig. 2a, Grison 1997). The methodology was thus validated as made previously for casting pores in single crystals (Defresne 1990, Remy 2013 b).

For practical use the cleanliness function $N_v(D>D_0)$, indicating the amount of particles per volume of size larger than a given value D_0 was obtained comparing the probability density function in Eq.1 with extensive fracture analysis of specimens tested in the database. Fig. 2b gives an example of curves that can be obtained for the probability of engineering crack initiation for LCF specimens and engine parts (Brethes 2000).

2.3. LCF and TMF life prediction of single crystal superalloy for high pressure turbine blades in aero-engines

The continuous increase of turbine inlet temperature in jet and aircraft engines has led to the increase of blade temperature and the increase of strengthening precipitate volume fraction γ' $Ni_3(Ti,Al)$. This has been made possible replacing conventional cast alloys by directional solidification into poly-crystal form and further into single crystal form. This was combined with improvement of cooling techniques and introduction of Thermal Barrier Coatings (see e.g. Guerre 2003, Rémy 2014, Courcier 2011). In early time the thermal gradient was low and components were designed against creep. Now thermal gradients are high and components need to be designed against TMF.

The first concern with single crystal blade is elastic anisotropy that is strong in nickel alloys, and then plastic anisotropy. LCF tests under isothermal conditions (Chieragatti 1991, Fleury 1993) were rapidly complemented by TMF tests using cycles extracted from computed missions estimated from component design. A simplified counter clockwise strain temperature TMF cycle test introduced earlier (Malpertu 1990) was used (Fig.1c, Fleury 1994). The crystal plasticity model of Meric (1991) was used that combines Schmid law and Chaboche type equation between the visco-plastic shear strain rate and the projected shear stress on individual slip systems. This model has been identified for various isothermal tests (Hanriot 1991, 1993) and described pretty well the stress-strain loop under TMF cycling (Fig. 1d, Hanriot 1993, Fleury 1994, Rémy 2003).

Once the crystal visco-plasticity model is identified, a damage model can be used in a post processor of the FE model (Cailletaud 2003). As the major orientation of the blade is near <001> direction of the face-centered cubic lattice of the superalloy matrix, one can use a macroscopic Chaboche type continuum damage mechanics model that assumes an equivalent stress based damage model combining creep and fatigue damage contributions (Chaboche 2000). Under thermal transient conditions, creep damage is obtained from simple time integration but for fatigue one has to use a stress normalized to the ultimate stress at the current temperature. The model yields very good description of the frequency dependence of tests in air and provides fairly good agreement with TMF tests.

Oxidation has been shown to very important for low frequency LCF in air in many cast superalloys (Coffin 1972, Reuchet 1983, Reger 1988, 1990). The frequency dependence disappears for tests carried out under vacuum (Coffin 1972, Reuchet 1983 a, Reger 1988 a and b). In cast alloys inter-dendritic oxidation gives rise to oxide spikes growing from the surface. Oxidation kinetic data based on metallographic observations on LCF specimens sections have been used to show that LCF life could be predicted (Reuchet 1983 b) using a summation equation as:

$$da/dN = (da/dN)_{fat} + (da/dN)_{ox} \tag{2}$$

The fatigue contribution is based on crack tip opening (Tomkins 1968, Chalant 1983, Chataigner 1996). High temperature LCF in nickel base alloys under air results in the formation of a complex oxide layer and a reaction zone depleted of strengthening precipitates in the adjacent substrate as in creep (Chateau 2010, Rémy 2003). Under thermal transients oxidation embrittlement can occur. This has been shown using LEFM tests on pre-cracked compact tension specimens that have been oxidized at high temperature without load (Rémy 2003). Such tests were done on superalloy single crystals (Rémy 2003, 2007). A significant zone is affected ahead of the precrack where FCGR increases drastically before recovering the value corresponding to the virgin material (Fig.3a). This means that a reduction of material properties can be achieved due to oxidation effects without load while creep- fatigue damage interaction requires stress. This is the basis of a TMF damage model (Rémy 2007).

The main damage cause in components is the occurrence of TMF and LCF cracks. Such cracks can nucleate at stress concentrations: casting pores at inter-dendritic areas or cooling holes. In both cases these defects have a size around or smaller than the size of primary dendrites (in the range 0.3 to 0.4 mm in most cases). Thus a micro-crack growth model is very attractive. Models (Chalant 1983) assume a process zone as introduced by McClintock (1963): it is often assumed to be a microstructure size. To check this assumption, the behavior of short cracks has been investigated in single crystals tubular specimens having a horizontal through notch 0.5 mm wide with a 0.05 mm tip radius. Tests were run under fully reversed strain at 950°C under small scale yielding conditions. Tests made at different frequencies for <001> and <111> orientations (Remy 2013 b, Bourbita 2016) have shown that in the notch vicinity a FCGR plateau is observed before recovering LEFM-behavior (Fig.3b). The FCGR in the plateau increases strongly with decreasing frequency. This anomalous regime was treated as an “engineering initiation period”. A crystal visco-plasticity model was used to compute the stress-strain field at the notch vicinity as done previously for long crack tips (Flouriot 2003, Marchal 2006). The anomalous short crack growth regime was shown to correspond to the plastic zone size and normal stress singular zone.

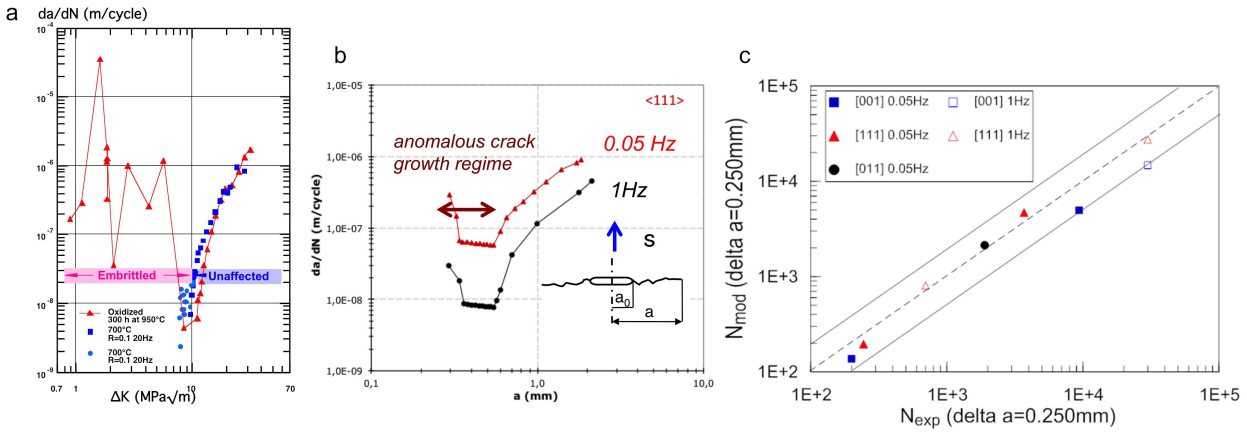

Fig. 3. (a) FCGR of pre-oxidized CT superalloy single crystal showing embrittlement in oxidation affected zone; (b) anomalous crack growth rate regime for a small notch (initial length 0.25 mm, notch radius 0.05mm) at 950°C in AM1; (c) comparison of crack initiation period in the notch affected zone obtained by oxidation-fatigue model at a critical distance and experiment.

Assuming a maximum principal stress criterion, the stress gradient can be treated as a normal stress at critical distance of 0.1 mm combining FE analysis and data of short crack data from smooth specimens under low frequency LCF (Fleury 1993). A model based on plastic dissipated energy density and dilation elastic strain energy (Maurel 2009) was used. Oxidation fatigue interaction in Eq.3 was described as oxidation-induced embrittlement. The model was calibrated on LCF data at high frequency and low frequency. It describes the whole crack growth curves in smooth specimens. In addition the life to initiate a 0.25mm crack at the notch can be predicted whatever the loading crystallographic orientation and frequency (Fig. 3c, Bourbita 2016).

2.4. Multi-scale approach: welded automotive hot parts

When dealing with some complex problems it is necessary to introduce a multi-scale approach. This was done recently for the design of automotive welded exhaust manifold made of 1.4509 ferritic stainless steel (Fe-18Cr-Ti-Nb). A FE component model was used at the macro-scale and a life prediction model has to apply at this scale. Tests were carried out on welded specimens tested under tension-compression. The specimens were machined from welded plates (about 2mm thick) with the weld bead perpendicular to the load axis. Observations of crack initiation and growth were carried out and damage model was identified with a FE model at this meso-scale (Benoit 2014). A shell model was introduced to describe the effect of the weld at the macro-scale. A fatigue criterion was then identified at the macro-scale using this weld model and damage identified at the meso-scale. The validation of constitutive model and damage model was made using TMF tests on welded specimens. The modeling chain was then used to predict component life under TMF cycling. The methodology is summarized in Fig. 4.

Isothermal LCF tests on weld specimens have shown that cracks initiate early at the geometric discontinuity between weld bead and base metal. Micro-crack growth occupies most of the lifetime (Benoit 2014) and FCGR is described by model using partition of strain energy density (Maurel 2009). This criterion was integrated at the macro-scale using the weld model and macro FE elements of mid-thickness size. Under TMF the criterion has to be integrated along the temperature cycle experienced by each element. Manifold was tested on bench until crack initiation around 1400 cycles. This lifetime was fairly well predicted using the proposed criterion and the maximum dissipated energy criterion used currently at PSA (Charkaluk 2000).

3. Conclusions

A significant progress has been achieved in assessing the LCF lifetime of components experiencing high temperature and thermal transients. An adequate database is essential to identify constitutive equations and damage models. Visco-plastic constitutive models can provide good predictions of overall deformation and local cyclic plasticity in FE analysis of components. Damage models based on short crack growth data under small scale yielding can be used when LEFM applies. Probabilistic models are necessary when rare defects are inherited from the process. Physically based models or continuum damage mechanics models are necessary when significant cyclic (visco-) plasticity prevails at high temperature. Creep and environmental effects should be considered.

Multi-scale approaches are promising for complex cases as shown for weld structures.

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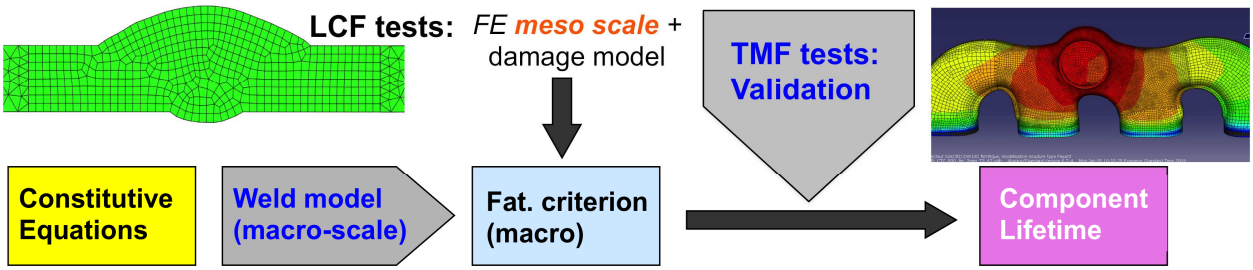

Fig. 4. Multi-approach of welded stainless steel exhaust manifold: LCF tests are used to identify damage and constitutive model; a damage model is identified at the meso-scale and integrated at the macro-scale in a weld model; TMF tests are used to validate the whole approach before application to the component.

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