CRACK GROWTH UNDER THERMO-MECHANICAL FATIGUE IN NICKEL CAST ALLOYS

Karl Michael Kraemer*, Falk Mueller and Matthias Oechsner

Technical University Darmstadt, Institute for Materials Technology, Darmstadt, Germany
** Presenting Author email: michael.kraemer@tu-darmstadt.de*

Abstract

This poster presentation summarizes the results from several projects in this field conducted at the TU Darmstadt to identify and describe the various influences on crack growth under thermo-mechanical fatigue (TMF) loading. The activation of damage mechanisms under TMF loading and interactions between them are dependent of the temperature cycle and the respective load phasing. Depending on the type of loading (force- vs. strain-control), contrary influences of the phase shift on the TMF crack growth rates are found. To describe crack growth under creep-fatigue and TMF conditions, the linear accumulation model 'O.C.F.' was developed - based on the contributions of fatigue, creep and oxidation to crack growth per load cycle. This model is capable to reproduce the effects of time-dependent damage, different load ratios and TMF phase shifts, as well as component geometries. The model's linear formulation allows assessing the dominant driver of crack growth at each stage of an experiment. These predictions are compared with fractographic investigations and in-situ observations of crack paths to identify the mechanisms of crack growth under different TMF load cycle forms.

1. Introduction

In the light of increasingly flexible operation conditions, gas turbine manufacturers and operators aim for damage tolerant design approaches. The basis for an application of such an approach is an experimentally validated description of crack growth. While most of the published investigations into the influences on TMF crack growth are based on force-controlled testing, under real service conditions the occurring TMF loading of components through thermally induced stresses is strain-controlled. The transfer of force-controlled measurements on components is questionable. In this paper, the results of recent studies on the subject of crack growth in nickel alloys at the TU Darmstadt are summarized. The quantitative effects of TMF phase shifts, hold times and loading mode on the crack growth rates under complex loading are adressesd in a parametric study and through comparison with isothermal FCG measurements. A modeling approach for crack growth rates under such complex loads is presented. The so-called "O.C.F."-model consists of a linear superposition of the crack growth fractions caused by the predominant damage factors active under TMF: oxidation, creep and fatigue.

2. Results

A series of TMF crack growth experiments was conducted as well under stress-controlles as under strain-controlled TMF conditions, to study the effect of stress ratio evolution and hold times on crack growth rates. In Figure 1a the results from multiple IP-TMF crack growth measurements with and without hold times are compared. Force-controlled IP-TMF crack growth with fixed $R_\sigma = -1$ and without hold time can be compared to isothermal crack growth at T_{max}. Introducing a 300 s tensile hold time accelerates the crack growth by a factor of 10. If the same experiment is conducted in strain-control mode, the measured crack growth rates are reduced by a factor of 10 and lie in the region of the isothermal behaviour at T_{min}. An introduction of a hold time under these conditions does not provoke significant crack growth acceleration. The values measured under strain-control can be reproduced by conducting a force-controlled experiment with a similar stress range (e.g. -2.3). However, if a hold time is introduced and relaxation is prevented by force-control the already mentioned factor 10 increase is measured again. Under force-controlled OP-TMF conditions with $R_\sigma = -1$, the measured crack growth rates lie slightly above the mean isothermal values for Tmin (Figure 1b). The effect of introducing a hold time under strain-controlled conditions remains unclear, due to the scattering in the measures crack growth rates. However, if the experiment is conducted under strain-control, the resulting tensile mean stresses increase the crack growth rates by a factor 5. This effect of the stress ratio can by reproduced under force-control conditions.

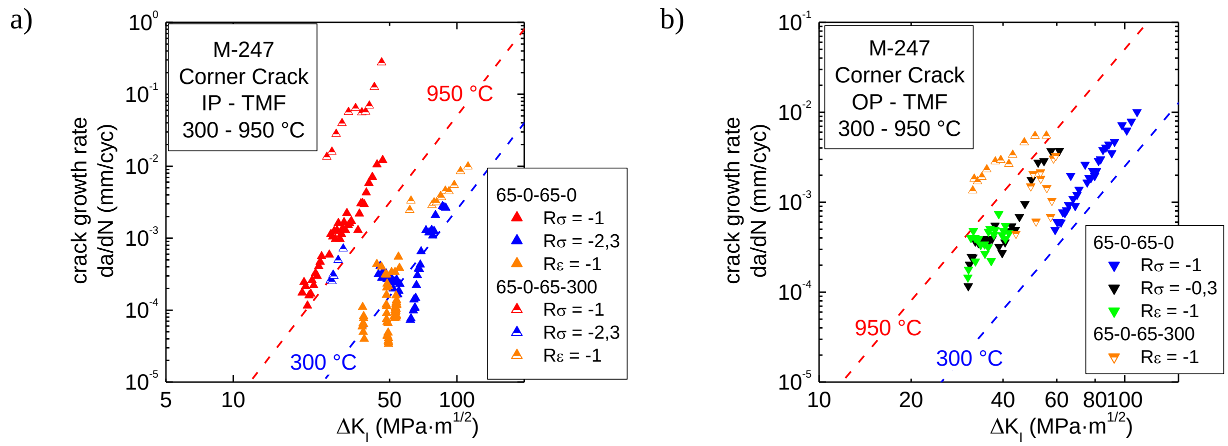

Figure 1: Influence of hold times and load ratio on crack growth rates under IP-TMF loading (a) and under OP-TMF loading (b)– dashed lines represent isothermal FCG at R_σ = -1 and 1-1-1-1 load cycle

To model TMF crack growth independent from the load cycle type, the mechanism-based accumulative 'O.C.F.' model was concived. Its main assumption is that, TMF crack growth can be described as a summation of fatigue crack growth, creep crack growth and oxidation:

$$da/dN_{\mathrm{O.C.F.}} = (da/dN)_{\mathrm{Ox}} + (da/dN)_{\mathrm{Cr}} + (da/dN)_{\mathrm{Fat}}$$

The formation of a γ'-depleted zone at the crack tip was identified to be the most relevant effect of oxidation in the case of precipitation hardened nickel cast superalloys. The recalculation of crack length over load cycles for a flat specimen of alloy M-247 under IP-TMF conditions is shown in Figure 2a. The shown accuracy of factor 1.5 in specimen life lies well within the model capabilities. The complete validation data base for the O.C.F. model consists of 35 CFCG and TMFCG test on alloy C1023 and 50 tests on M-247 cast variants. This includes test under force- and strain-control, with and without hold times, on corner-crack, flat specimens with bore holes and hollow specimens with bore holes. The majority of the results lie within a scatter band of factor 3. The M-247 data base also includes single crystalline and directionally solidified cast variants, all fitted with one set of parameters. The viability of this modelling technique has been shown for three different nickel-cast alloys up to now.

3. Conclusions

A detailed comparison of crack growth rates measured from different combinations of TMF phase shifts, loading modes and hold times shows that the evolution of stresses during an experiment governs the resulting crack propagation. While tensile hold times have a large impact under force-controlled conditions, the resulting relaxation under strain-control may reverse this effect. To prevent substantial over- or underestimations of crack growth rates under service conditions, the loading mode must be chosen accordingly. With the O.C.F.-model, a damage mechanism-based linear summation approach, it is possible to give predictions for the crack growth in nickel-cast alloys both under isothermal and TMF loading. The model reproduces the effects of hold times, stress ratios and phase shifts correctly and recalculates crack growth rates and crack evolutions accurately, within the range of the material inherent scattering.

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