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A modified compliance method for fatigue crack propagation applied on a single edge notch specimen

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ABSTRACT

Crack length measurements with high accuracy are often difficult to achieve during fatigue crack propagation testing under non-isothermal conditions. In this work a modified approach to the compliance method defined in e.g. ASTM E647 is described, which is better suited for high loads, varying temperatures and for taking the scatter in Young's modulus into account. A numerical finite element study is performed for a single edge notch specimen, to investigate the influence of initiation locations on the accuracy of the method. The change in cracked area versus change in stiffness for three different cases are numerically shown to collapse to one curve, i.e. the result is not significantly affected by how the crack is initiated. The numerical study is compared to results from two experiments using different materials, with heat tinting during the tests for extracting snapshots of the crack fronts. A good agreement between the experiments and the numerical study is shown. A new compliance curve and a new geometry function for the stress intensity factor is proposed for the single edge notch specimen.

1. Introduction

For assessment of the total life of a gas turbine component, it is very important to acknowledge both the crack initiation and propagation parts [1,2]. In many situations a stable crack propagation part occurs after initiation until the component fails, and not addressing it generally leads to too conservative designs.

For loadings under linear elastic fracture mechanics (LEFM) situations, the stress intensity factor, K, and its range, can be used to predict the life via Paris' law [3], shown in its simplest form in Eq. (1).

$$\frac{da}{dN} = C \cdot (\Delta K)^m \tag{1}$$

where C and m are material constants which need to be experimentally determined. The stress intensity factor is a function of applied load, crack length and a geometry factor [1,2].

For situations with high loads and plasticity, Dowling and Begley [4] showed similarly to what Paris had shown for ΔK, that there is a linear relationship between cyclic J-integral, ΔJ [5,6], and the crack growth rate da/dN in a log-log plot, see Eq. (2).

$$\frac{da}{dN} = D \cdot (\Delta J)^n \tag{2}$$

where D and n are material constants which also need to be experimentally quantified. ΔJ or cyclic J is a function of applied stress-strain range and the geometry. It should be noted that even though the material constants shown in Eqs. (1) and (2) are not the same, a relationship coupling the parameters in the two equations can be found, cf. [10,7–9].

In fatigue crack propagation testing it is essential to measure the crack length with high accuracy independently of which crack parameter (ΔJ or ΔK) that is utilised. Measurement of fatigue crack growth rates under isothermal conditions is a well-established technique which has been covered by standards such as ASTM E647 [11] since the mid seventies. Crack lengths are normally measured by either the compliance technique [12,13] or by the use of the potential drop method [14,15]. Regarding non-isothermal conditions standards are only available for testing of smooth specimens, such as ASTM E2368 [16] or ISO 12111 [17], which can be used for the determination of crack initiation life but cannot be used for generation of thermo-mechanical fatigue (TMF) crack propagation data. In fact, only a limited number of published studies on crack propagation under TMF conditions are available. This is probably due to the fact that mechanical testing under dynamic temperature conditions is somewhat more complex than

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isothermal testing techniques. Pioneering work on TMF crack propagation testing were conducted by Leverant and co-workers at Pratt & Whitney Aircraft in the 1970s [18–20] and by Okazaki and Koizumi in Japan during the 1980s [21,22]. In these early studies optical methods were used to measure the crack lengths. The main limitation with optical methods for crack length determination is that the method is limited to observations of the surface of the crack while it is preferred to have through thickness information of the crack length in order to account for tunnelling effects that often occur when dwell times are introduced at elevated temperature, cf. [23]. In later studies, performed mainly by NASA, induction heating was used together with the potential drop technique to measure crack lengths during TMF tests [24–27]. In order to get satisfactory results with the potential drop technique when induction heating is used, the electrical noise from the induction system needs to be filtered and the calibration curve needs to be properly corrected in order to take into account the changes of potential with temperature [24]. This is a procedure which is not straight forward and needs to be addressed carefully, but has been successfully used in recent studies, cf. [28,29].

An alternative method for crack length measurements during TMF testing, based on the compliance method, has been proposed by Moverare and Gustafsson [30]. The main benefits by using this method is that; (1) one can avoid the drawback with optical methods where only the surface can be observed during the test, instead an average through thickness crack length is measured similar to when potential drop is used, (2) one can avoid the difficulties with noise filtering from the induction heating, and (3) a simpler experimental set-up can be used since crack length measurements are based on load and displacement curves, where displacement is measured by a high temperature extensometer which is normally integrated in all TMF-systems. The standard describing the compliance method is given by the ASTM Standard E647. This method utilises the fact that the crack changes the stiffness of the tested specimen as it extends. Usually a dimensionless analytical relationship for the compliance is correlated to the crack length, see cf. [12]. Similar to the potential drop method the compliance curve has to be calibrated for each test based on a known crack length for a certain specimen compliance or stiffness. Moverare and Gustafsson [30] proposed that for TMF crack propagation tests with no pre-cracking, the drop in stiffness can be normalised by the uncracked stiffness in order to generate a generic compliance curve which can account for e.g. the large inherent scatter in Young's modulus due to large grain sizes and especially the temperature dependent stiffness change during TMF conditions. However, in [30] an experimental approach for the compliance curve for the investigated single edge notch specimen up to only 3 mm of crack length was derived based on fracture surface inspections, and a first order approximation was made in order to take the crack front curvature into account. In a later study by Ewest et al. [31], on the same specimen geometry, the compliance curve was experimentally extended for non-linear material behaviour and longer crack lengths, but calibrated for visual crack lengths, i.e. not compensated for curved crack fronts. Obviously, there is still a need for further validation of the procedure but more work is also needed in order to account for curved crack fronts, longer crack lengths and also different crack initiation locations at the notch.

The aim of this paper is to investigate a general method for crack length measurement which is suitable for TMF crack propagation situations with dwells (hold times) at high temperatures. This is done experimentally using room temperature fatigue propagation testing with interruptions for heat tinting cycles to evaluate the crack fronts during the crack growth. The results are also verified numerically using finite element (FE) 3D analyses and compared to previous published results. Furthermore, the impact on geometry solution in the stress intensity factor is investigated.

2. Experiments

Two different polycrystalline nickel-based superalloy materials, wrought Haynes 230 and cast Inconel 792, was used in the experimental crack length measurements. Haynes 230 is often used in wrought form for combustor applications, while Inconel 792 is used in precision cast turbine blades. Haynes 230 has the chemical composition Ni-22Cr-14W-2Mo-3Fe-5Co-0.5Mn-0.4Si-0.3Al-0.1C-0.02La-0.015B (wt.%), and has an approximate grain size of 55 μm. Inconel 792 has the chemical composition Ni-12.4Cr-8.9Co-1.8Mo-4.0W-3.5Al-4.0Ti-4.1Ta-0.08C-0.017B-0.019Zr (wt.%), and an approximate grain size of 1–2 mm.

Both materials where delivered as round bars and machined to the specified geometry. In Fig. 1 the drawing is shown for the studied SEN specimen. The geometry is a round bar with a machined flat surface containing a notch with a radius of 1 mm at a depth of 3 mm. The notch radius is large compared to common machined starter cracks in standard test specimens [11], but is chosen to resemble stress concentrations found in gas turbine components.

In Fig. 2 the test set-up, with the servo-hydraulic TMF testing machine is shown. The strain was measured with an extensometer mounted over the notch with a nominal gauge length L_0 of 12 mm. The strain is defined as $\Delta L/L_0$ and the stress σ is defined as the force F divided by the uncracked cross-section area A_0 at the notch, i.e. smallest area of the test specimen. The uncracked area is measured for each test specimen before the test is initiated.

According to ASTM E647 the compliance measurements shall be done by fitting a straight line to the upper section of a complete stress-strain cycle (above the crack opening location) including both loading and unloading, where the response is normally linear in an LEFM isothermal fatigue crack propagation test. For the current investigation a modified method is utilised, where the modification consists of the following important points:

- A compliance curve that correlate the change in stiffness to crack length is required. This is obtained from a 3D FE analysis. The crack length is expressed in terms of the cracked stiffness K normalised by the uncracked stiffness K_0.
- From the test data, extract the stiffness at the same location on the unloading part of hysteresis loop in each cycle, which gives the same temperature dependency on the stiffness for all cycles in the complete test, see Fig. 3. Thereby, any non-linear material behaviour or hold times will not influence the stiffness calculation.
- Normalise the cracked stiffness with the uncracked, to obtain the change in stiffness in the test. Thereby, any temperature dependency and/or material scatter will be removed and no post mortem investigations for calibration of each test is needed. It must be noted that Young's modulus is a property that show a very large scatter, especially for course grained materials as Inconel 792. Not properly accounting for that leads to large errors in the evaluation.

The modification is made because in TMF testing the temperature is varying, which is accompanied by temperature dependent stiffness changes, and during strain controlled testing in the elasto-plastic regime the situation becomes problematic. The non-linear response of the test specimen on the loading part can influence the stiffness evaluation to a large extent. Moreover, if any hold times are applied during the fatigue cycling this will furthermore effect the stiffness calculation, if the complete upper section (above crack opening location for both loading and unloading) of the stress-strain loop is considered. However, as the unloading from any inelastic (or elastic) state is always elastic, only the initial portion of the unloading part should be evaluated. It is to be noted