THERMOMECHANICAL CRACK INITIATION AND EARLY GROWTH IN 1CrMoV NOTCHED SPECIMENS

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ABSTRACT

Thermomechanical service-like experiments on 1CrMoV turbine steel are presented and the results are discussed with particular attention to crack initiation and early growth. Service-like means that (i) the strain and temperature control profiles correspond to the loading cycles expected in transient operating conditions of turbine components; (ii) the testpieces contain stress raisers (notches) similar to stress concentrating features in turbine components. Isothermal (N-LCF) and thermo-mechanical fatigue (N-TMF) tests have been performed on circumferentially notched bars. The main purpose of the investigation has been to evaluate the suitability of uniaxial fatigue data for the damage assessment of components with stress raising features. Service-cycle N-TMF tests (with low strain rates and long hold periods at peak temperature) reproduced at the notch root the strain and temperature histories of corresponding uniaxial TMF tests performed in previous studies. It is therefore possible to directly compare the notch root endurances with uniaxial data lines. The experimental results have been complemented by detailed finite element calculations and metallurgical analysis from post-test inspections. Under the assumption of a very short crack initiation length, the endurances of the notched tests can be rationalized from the uniaxial data. Measurements of short crack growth within the notch near field have been analysed using stress-strain loops in the notch near field calculated by finite elements. For the same surface equivalent strain range short crack growth is slower in notched tests than in uniaxial tests and is faster in the present N-TMF tests as compared with the N-LCF tests. Further understanding of creep-fatigue crack initiation and growth in turbine component features is expected from a novel approach to thermomechanical testing, which uses large three-dimensional testpieces. First tests are currently running. The experiment will be described and available results will be presented in this talk.

1. INTRODUCTION

The lifetime calculation of turbine components traditionally uses the results from uniaxial, isothermal low cycle fatigue (LCF) tests conducted at (or close to) the peak turbine operating temperature, see e.g. Timo [1]. This approach is applied also for the analysis of creep fatigue damage interaction at stress concentrating features, where (i) the stress state is multi-axial; (ii) significant strain gradients are present; (iii) the loading history is an-isothermal and is characterized by low strain rates ($\sim 10^{-5}$ /s) and significant hold periods at the peak cycle temperature. “Safety factors” may be applied in the mechanical design in order to compensate for the differences between component features and testpieces in uniaxial, isothermal tests, in terms of stress state and loading history.

The work presented in this paper is part of a comprehensive research project aiming to (i) improve the lifetime calculation of turbine components and (ii) provide further understanding of the interaction of creep and fatigue damage in component features during operation. In the first part of the project, Masserey [2], Holdsworth [3], the assessment of service-like loading cycles in 1CrMoV steel has been studied in uniaxial tests. In the present work the creep-fatigue lifetime assessment of stress concentrating features is investigated.

Notched specimen LCF and TMF (N-LCF, N-TMF) tests are described in section 2. For the N-TMF tests the temperature and loading histories at the notch root were similar to the service-like TMF cycle type applied in uniaxial tests [2,3]. The endurances from these tests can therefore be directly compared with uniaxial LCF and TMF data, thus yielding information on the applicability of uniaxial data to the assessment of components with stress raisers in service. The experimental data, endurance and short crack growth rate, are presented and analysed in section 3 using the results of non-linear finite element (FE) calculations that provided the stress-strain histories at the notch root and in the notch near field, see Mazza [4].

Section 4 discusses the results of this study and presents a novel approach to thermomechanical testing, called 3D-TMF, in which thermal stresses are generated in a large three-dimensional probe. The 3D-TMF experiments are currently running and might provide further understanding of crack initiation and growth at turbine component features in service.

2. EXPERIMENTS

The circumferentially notched cylindrical bar is shown in Figure 1A. The notched testpiece has a semi-circular groove with notch root radius R =1.144 mm, a minimum section radius of c=6.35 mm and a shank radius of b=7.5 mm. The gauge length (distance between the extensometer probes) is L=12.5 mm.

Tests were performed by controlling the axial displacement of the gauge length and the temperature profile. Specimens were equipped with axial and diametral extensometers. Heating was by means of RF induction. Crack development was monitored by potential drop (PD) technique, the voltage output being calibrated from the results of post-test inspection. The PD probes were mounted across the notch root and were supplied with a steady current of 60 amps. The isothermal test was performed at 550°C, with a gauge length displacement range expected to yield a notch root strain range of approximately 1%, and the FE analysis yielded a strain range of 0.9%. The LCF test was conducted at a frequency of 1 cycle per minute. The control profiles of the TMF cycles are described in Mazza [4] and were characterised by an an-isothermal loading history (reproducing transient phases of start-up and shut down), low strain rates and significant hold periods at the peak cycle temperature (to represent a steady running period). The control profiles of TMF cycles 1 and 2 (N-TMF1 and N-TMF2) were expected to yield notch root strain ranges of approximately 1.5% and 3.5% respectively. These strain ranges are larger than the ones expected for turbine component features in practice and were selected to give a total duration of the experiments of less than 2 weeks. Local strain ranges of 1.3% and 3.8% were determined from the FE calculations for N-TMF1 and N-TMF2 respectively, Mazza [4].

Post test metallographic inspection indicated that cracking was already broad front and fully circumferential by the time it had penetrated to a depth of 0.7mm. Crack development from the notch root in the N-LCF test was fatigue dominated. In the N-TMF tests, cracking was also predominantly fatigue dominated but with evidence of associated creep damage (Figure 1B). There was significant evidence of oxidation in the notch roots of N-LCF and N-TMF testpieces.

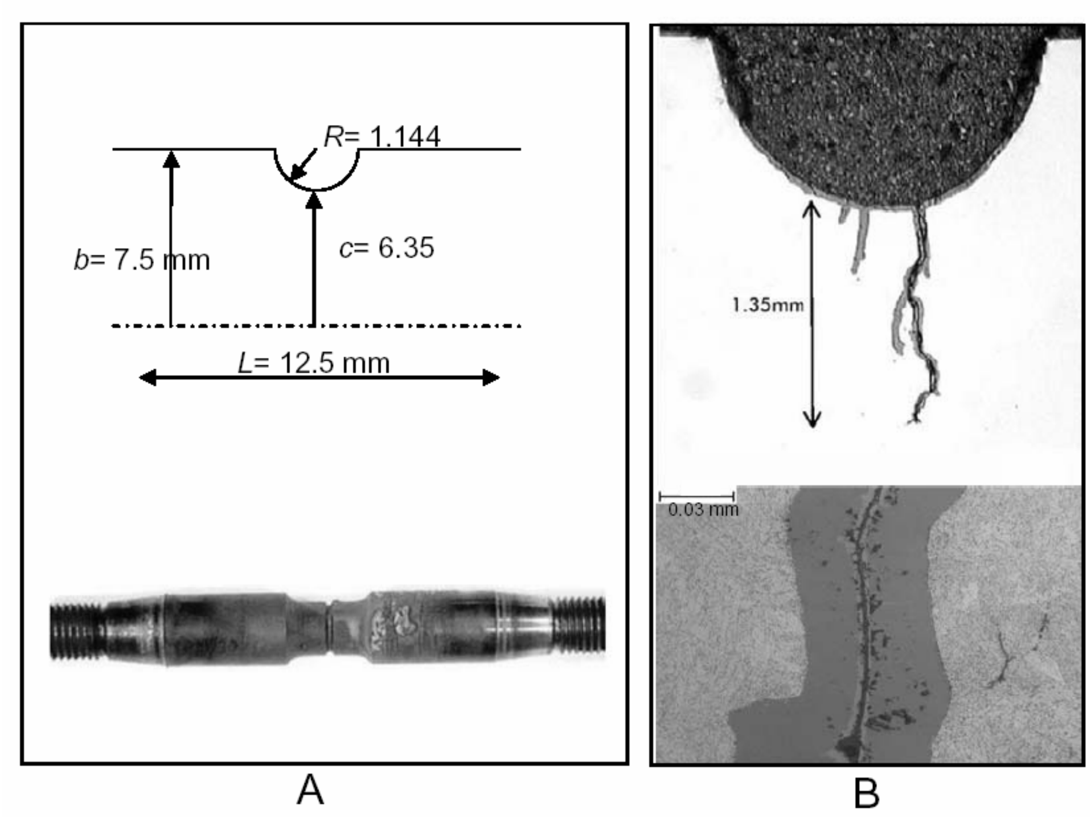

Figure 1: A: Testpiece geometry; B: evidence of cracking and creep damage after 165 cycles

3. DATA ANALYSIS

3.1 Endurance

In Figure 2A the notched LCF test endurance is compared with isothermal 550°C LCF continuous-cycle data line for this steel. Endurance to 0.1 mm and 0.5 mm crack size and crack size evolution are reported for notched and plain LCF test performed with the same material (same heat). In the case of the uniaxial test the crack size was not directly measured, but determined from a FE calculation of the testpiece compliance as a function of the crack size and the measurements of "load drop" during the test. Endurances expressed as number of cycles to crack initiation require the definition of a crack initiation length (criterion). Good agreement between uniaxial and notched endurances is found for a crack initiation length of 0.1 mm.

The endurance of the notched TMF cycles is compared in Figure 2B with the LCF cyclic/hold line (1 hour dwell) at 565°C for this material. Endurances corresponding to 0.1 and 0.5 mm crack initiation length are reported for the notch root strain ranges. As in the case of the LCF test the endurance of the notched TMF tests can be rationalized on the basis of uniaxial endurances for a crack initiation length of 0.1 mm.

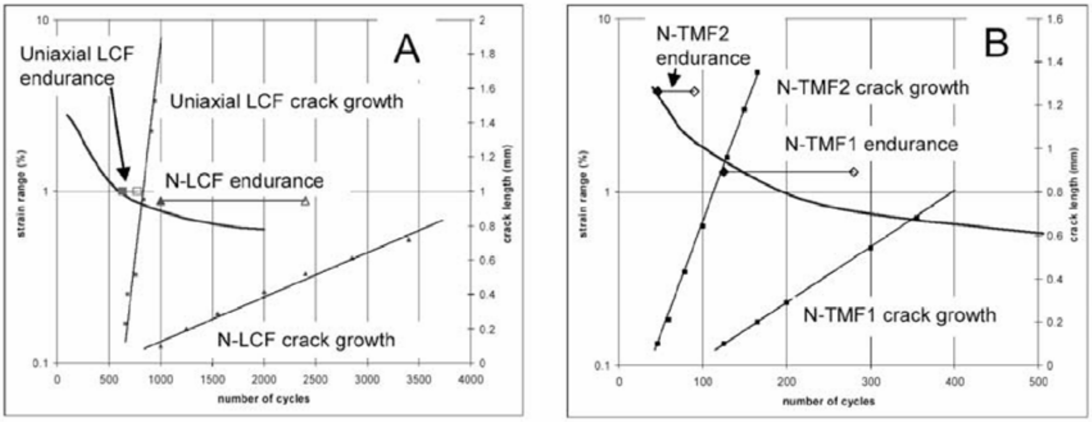

Figure 2: Endurance and crack length evolution. A: comparison of N-LCF with uniaxial LCF test. B: results for N-TMF tests. Open symbols: crack initiation length = 0.5 mm. Full symbols: crack initiation length = 0.1 mm

3.2 Short crack growth

The results of 3.1 suggest that crack initiation at the root of a stress concentration in a turbine component can be predicted from the endurances of uniaxial tests using a very short crack initiation length (criterion). Considering that the size of a detectable crack is > 1 mm and the critical size for a surface crack in a turbine component is typically in the range of several mm, the prediction of the growth of short cracks in the notch near field (from 0.1 to 0.5 – 1 mm length) might have to be included in the lifetime calculation.

Crack advance within the notch near field is influenced by the decrease of current strain range. Crack growth in the present tests is analysed using an approach based on the strain range of the uncracked specimen, Skelton [5]. In particular, the following empirical relation is used, Skelton [6]:

$$da/dN = B \cdot a^{Q} \qquad (1)$$

where B depends on the total strain range, $B(\Delta\varepsilon)$. The application of this method for the crack growth calculation in turbine components requires the knowledge of the material parameters Q and $B(\Delta\varepsilon)$. From the present tests the influence on B of low strain rate and hold time in an-isothermal loading cycles can be evaluated. From Skelton [6], Q=1 is assumed in the following analysis. Based on the crack growth measurements and the total equivalent strain ranges from the FE calculations, values of $B(\Delta\varepsilon)$ can be determined from each test. For each crack length the local value of strain range $\Delta\varepsilon(a)$ is known from the FE calculation and the value of B is determined from eqn (1) (da/dN is derived from the curves reported in Figure 2). The results for N-LCF and N-TMF tests are reported in Figure 3. The points from the N-LCF test lay consistently below the values obtained from the N-TMF tests, for a given cyclic strain. The comparison for a strain range of approximately 1% yields a factor of 3 larger B values for the N-TMF tests. The enhanced crack growth rate in the N-TMF tests are due to the additional creep damage accumulated during the hold time at peak temperature, as indicated by the findings of post-test metallurgical inspection.

From the crack growth data of the uniaxial LCF test reported in Figure 2 a crack growth rate is evaluated for a= 0.5 mm. The corresponding value of $B(\Delta\varepsilon=1\%)$ is calculated from eqn (1) and is reported in Figure 3 (open point). This point lines up fairly well with the points obtained from the N-LCF test.

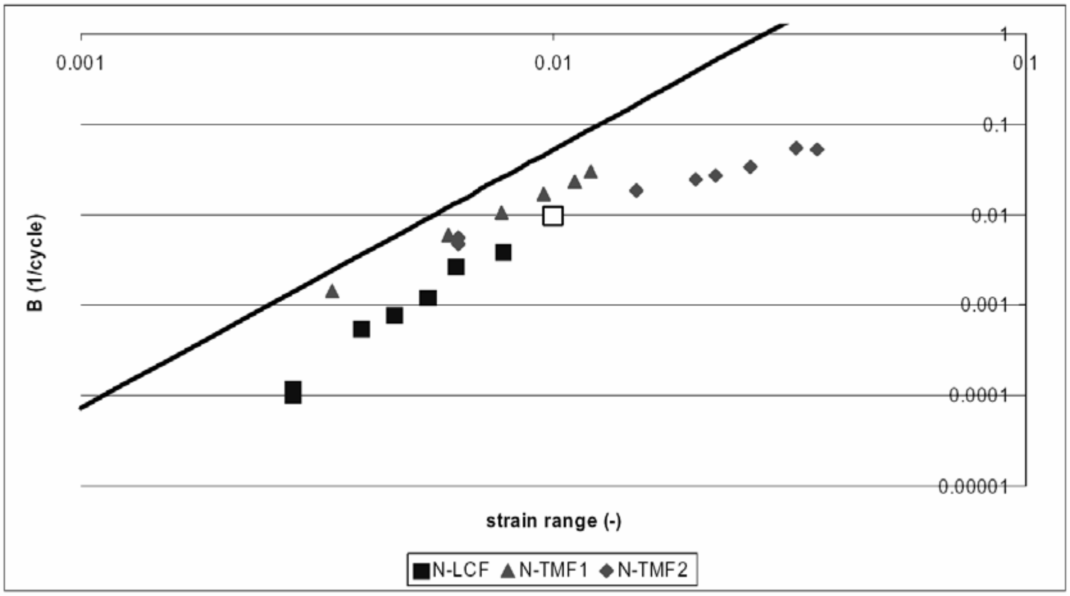

Figure 3: B-values from N- LCF and N-TMF tests

4. DISCUSSION AND OUTLOOK

The number of cycles to crack initiation in N-LCF and N-TMF tests can be rationalized with uniaxial fatigue endurance data. Good agreement with uniaxial endurances was obtained for a crack initiation size (criterion) of 0.1 mm. The endurance for a crack initiation size of 0.5 mm differs approximately by a factor of 2 from the 0.1 mm crack size endurance. The practical implications for the lifetime assessment of turbine component features are:

- uniaxial endurance data can be used for the calculation of number of cycles to crack initiation at the notch root,
- the corresponding crack initiation size (criterion) is in the range of 0.1 mm,
- consideration of crack development in the short crack development regime may be necessary in the calculation of the useful component lifetime.

Crack growth in notched testpieces is significantly slower than in uniaxial testpieces for the same nominal strain transient. Measurements of crack growth rate combined with a knowledge of the strain range variation in the notch near field allow the determination of a $B(\Delta\varepsilon)$ relationship, which can be used in eq.1 for calculating short crack growth. Note that, in contrast to notched tests, one single point of the $B(\Delta\varepsilon)$-curve can be obtained from uniaxial tests. Service-like N-TMF cycles lead to larger values of B as compared with the value determined from isothermal tests, this being in agreement with the observed enhanced creep cavitation density in N-TMF experiments.

The stress and strain fields at the notch of the testpiece of Figure 1 differ from the conditions expected at turbine components in terms of (i) gradients and (ii) triaxiality. A new type of thermomechanical test (3D-TMF) has been developed in which notch gradients and stress triaxiality are more representative of service-like conditions. The testpiece for this experiment is shown in Figure 4. It is a large three-dimesional probe (approx. 60 Kg, 1CrMoV) whose geometry has been optimised through iterative FE calculations in order to reproduce at specific locations the stress and strain histories expected at critical locations of turbine components in service. Large temperature gradients are generated in the probe using a special furnace, with powerful heating and cooling plates. Temperature gradients are monitored by means of multiple and periodic bulk measurements via sheathed type K thermocouples. First experiments are currently running. The methods applied for crack detection and monitoring as well as the available results in terms of endurance and crack growth will be presented at the conference.

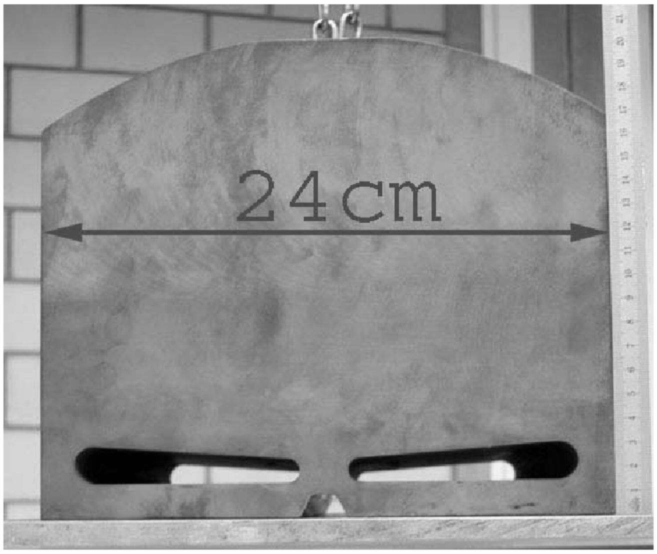

Figure 4: Probe for 3D-TMF test.

REFERENCES

[1] Timo, D.P., ‘Designing turbine components for low-cycle fatigue’, Proc. Int. Conf. on Thermal Stresses and Fatigue, Berkeley, 453, 1969.

[2] Masserey, B., Colombo, F., Mazza, E., Holdsworth, S.R., ‘Factors influencing the service-like thermo-mechanical fatigue test cycle endurance of 1%CrMoV rotor steel’, Fatigue & Fracture of Engineering Materials & Structures, 26, 1041-1052, 2003.

[3] Holdsworth, S.R., Mazza, E., Jung, A., ‘Creep-fatigue damage development during service-cycle thermo-mechanical fatigue tests of 1CrMoV rotor steel’, Proc. 9th International Conference on The Mechanical Behavior of Materials, Geneva, Switzerland, 2003.

[4] Mazza E., Hollenstein M., Holdsworth S.R., Skelton P.R., ‘Notched specimens thermo-mechanical fatigue of a 1CrMoV turbine steel’, submitted to Nuclear Eng. and Design, 2004.

[5] Skelton, R.P, ‘Growth of short cracks during high strain fatigue and thermal cycling’, Low Cycle Fatigue and Life Prediction, ASTM STP 770, Eds. C. Amzallag, B.N. Leis and P. Rabbe, American Society for Testing and Materials, 337-381, 1982.

[6] Skelton, R.P, ‘Application of Small Specimen Crack Growth Data to Engineering Components at High Temperature: A Review’, Low Cycle Fatigue, ASTM STP 942, Eds. H.D. Solomon, G.R. Halford, L.R. Kaisand and B.N. Leis, American Society for Testing and Materials, 209-235, 1988.