GROWTH AND COALESCENCE OF MULTIPLE CRACKS – EXPERIMENTS AND FRACTURE MECHANICS BASED MODEL

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Abstract
Short crack growth tests are carried out on the coarse-grained nickel-based cast alloy Iconel 100 (IN100) and two microstructures of the austenitic stainless steel AISI 347 using the replica technique. IN100 is tested under TMF and AISI347 isothermally. For both materials, several cracks are found which grow together to form the final main crack. Atypically, the final main crack length does not develop exponentially. To describe the damage evolution of the final main crack, a model is developed based on inelastic fracture mechanics, which includes the different crack driving forces along the crack front, and applied to the test results.

1. Introduction
A large percentage of damage cases is caused by fatigue. In order to avoid this or to choose the maintenance intervals accordingly, it is of great importance to understand the crack growth and to recognize mechanisms under the respective load and the respective microstructure. The replica technique is particularly well suited for the experimental monitoring of crack growth and damage development. With this method, the entire surface of the specimen is imaged, making it possible to detect possible secondary cracks on the originally smooth specimen. On the investigated specimens made of two different materials with three different microstructures, a large number of cracks were found which grew independently of each other in the beginning of the experiments, and some of these grew together to form the final main crack that led to failure. The microstructure has a decisive influence on the observed multiple crack growth under TMF and isothermal loading. The developed model, which uses the measured cracks as input and incorporates the different crack driving forces along the crack front, is able to reproduce the multiple crack growth and explain the damage evolution.

2. Results
TMF tests were carried out on originally smooth specimens of the coarse-grained nickel-based cast alloy IN100 using the replica technique and on the austenitic stainless steel AISI 347 under isothermal conditions. The tests showed that in both materials many cracks formed and partially grew together during the course of the test. Initially, more and more cracks formed and grew independently of each other. At about half of the lifetime, the maximum number of cracks was reached and decreased from then on due to the coalescence of several cracks. This multiple crack growth dominates the damage development.

The investigations on IN100 (grain sizes approx. 250-1200 µm) under TMF showed that, the phase relationship (IP or OP) and maximum temperature (thermal cycles investigated: 300-850 and 300-950 °C), have a big influence on the number of cracks forming the final main crack and the maximum crack lengths. The final main crack formed perpendicular to the loading direction with more or less strong local deviations depending on the loading. With IP loading, the crack was strongly oriented along the microstructure, which led to large local deviations, and under OP loading to a lesser extent. In the case of AISI 347 at 180 °C, more and shorter cracks formed on the specimen surface with the small grain size (11 µm) than with the large grain size (45 µm) for both investigated strain amplitudes ε_a=0.35 and 0.5 %, while the lower amplitude led to less cracks than the higher.

To evaluate the damage development and to investigate the influence of multiple crack growth, the parameter $2c_{rel}$ is defined: the sum of all crack lengths which grew together to form the final main crack related to the final main crack length. For the loads investigated, an atypical non-exponential crack growth for $2c_{rel}$ was found for the final main crack.

Based on the damage parameter D_{TMF} for IN100 and the cyclic crack tip opening ΔCTOD for AISI 347, a model was developed to describe the multiple crack growth. In the case of coalescence, the surface crack length of the coalesced crack is calculated as the sum of the two individual cracks and the crack depth is assumed to be the one of the two that is smaller. The cracks measured perpendicular to the loading direction, which led to the final main crack at the point in lifetime when most of the cracks were present, are used as the initiation parameters. Crack initiation is thus not taken into account.

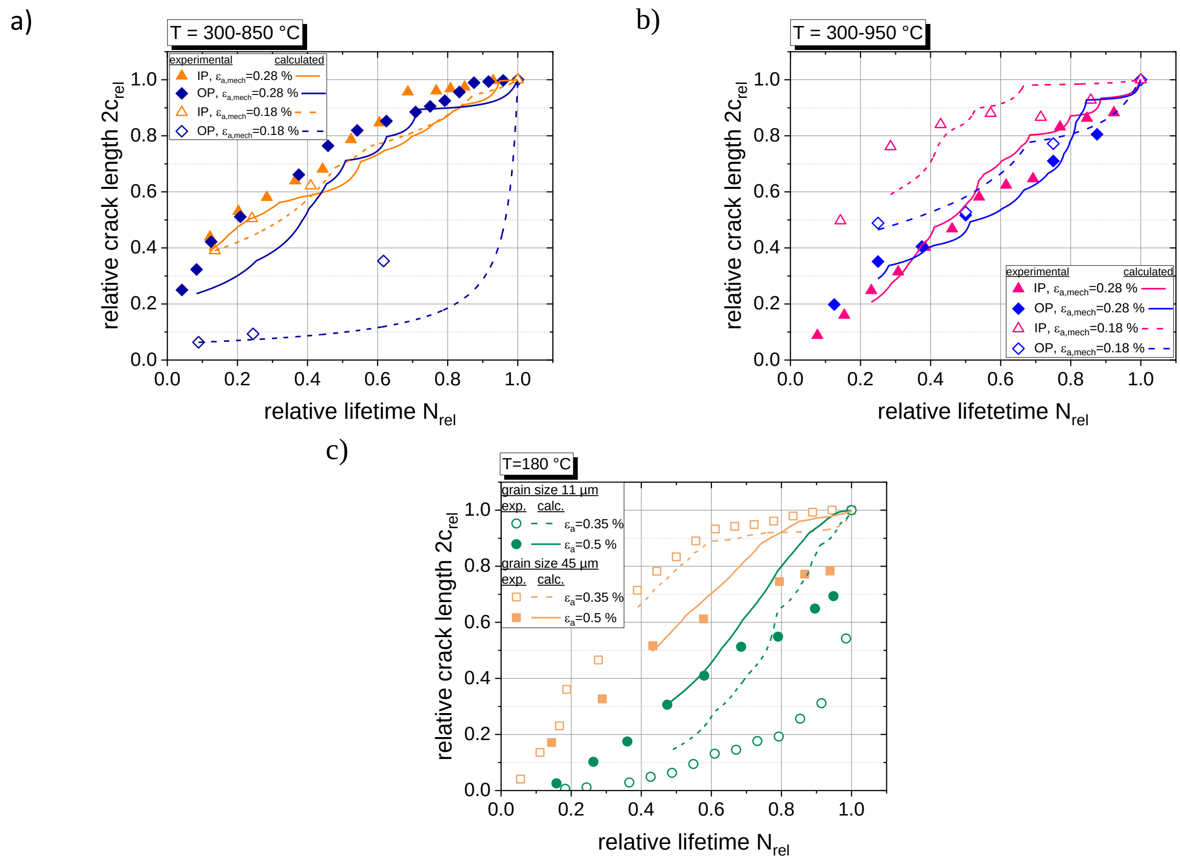

Fig.1 – Experimental versus calculated damage development of a) IN100 under thermal cycle 300-850 °C; b) IN100 under thermal cycle 300-950 °C; c) AISI 347 at 180 °C.

The application of the developed model shows that crack growth can be modeled for all cases investigated (Fig. 1). The coalescence of cracks leads to a slowdown of the surface crack growth. For the modeling, elliptical cracks, which could also be observed on fracture surfaces, are assumed and show different crack driving forces along their crack front. Since a crack tends to have a significantly longer surface crack length than crack depth after coalescence, the crack driving force after coalescence of two cracks is larger in depth than at the surface. This leads to a slowdown of the surface crack growth and thus to the observable non-exponential damage development.

3. Conclusions

The multiple crack growth observed in experiments for different materials and microstructures under different loads and the resulting atypical damage development can be reproduced and explained by the developed fracture mechanics-based model.

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