THE INFORMATION CONTENT OF QUANTITIES THAT DESCRIBE SURFACE CRACK PATTERNS

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A complex pattern of branched irregular surface cracks develops during thermal cyclic loading of smooth austenitic steel plates. Geometrical simulation models for initiation and propagation of cracks were used to assess and to understand the different stages of damage evolution. For this purpose, experimentally obtained patterns of cracks were analysed and the results of the analysis were compared with the outcome of the simulation. It turned out, however, that mean value quantities are less sensitive to different mechanisms of crack propagation than expected. Empirical distributions are preferable, but more difficult to obtain. The effect of changes in simulation parameters on the behaviour of characteristic quantities of crack patterns is investigated and implications are addressed for the statistical analyses of crack patterns

INTRODUCTION

Under cyclic thermal loading, initiation of cracks on the specimen surface leads to the formation of irregular patterns of kinked and branched cracks of complicated shape. This damage process was analysed for an austenitic stainless steel (German designation 1.4948) in [1]. An example of such a crack pattern is shown in Fig. 1 of Ref [2]. A stochastic simulation procedure was developed in order to assess the different stages of crack initiation, propagation, and coalescence [3]. Characteristic quantitities were defined which allow to compare different crack patterns in a quantitative way. Different classes of characteristic quantities were used corresponding to increasing levels of sophistication. Starting with quantities denoted by „simple crack statistics“ which are related to number, total and individual size of cracks we proceeded to more advanced quantities which reflect the underlying model of crack formation and propagation along pre-defined paths, the so-called model-based crack statistics. These quantities use features of the stochastic model for the evolution of crack morphology. By this way, it was felt that a deeper understanding may be gained of the importance of crack interaction and branching and of the influence of these processes on the resulting crack patterns. Several

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simulations were performed with in which underlying stochastic model was varied the resulting changes of selected characteristic quantities of crack patterns were analysed. This paper will first give an overview on the modelling and the quantities we use and then present their application to the evaluation of simulated as well as experimentally obtained patterns. Uncertainties in data collection will be shortly addressed. A comparison between two simulated and one experimental pattern will serve as example to show the possibilities and limitations of the proposed approach. It will also give some idea on the information content of quantities which are usually employed for damage evolution in case of multiple crack damage.

MODELLING AND CHARACTERIZATION OF RANDOM CRACK PATTERNS

Photographic images of the damaged surface were taken after a given number of thermal load cycles. The photos (see e.g. Fig. 1 in [2]) showed crack patterns of random nature. Statistical characteristic quantities are therefore required for evaluation purposes. We can imagine different levels of modelling, which correspond to different classes of quantities as shown in Table 1. Simple crack statistics is applicable in any situation, for simulated as well as for experimentally obtained patterns. More advanced quantities make use of specific features of crack propagation models. In Table 1, two examples are given to illustrate the modelling background. As a first trial in a very early stage, propagation of cracks was modelled by a fibre process that is, by generating line segments with random length and orientation [3]. Very quickly, it became evident that the crack patterns obtained in this way were not in agreement with experimental findings. The characteristic

level of modelling	**pattern-related quantities**	**crack-related quantities**
simple crack statistics	• number of cracks • cumulative crack length	• length of a single crack
fibre process model	• orientation angle of a crack segment • estimate of cumulative crack length • pair correlation function of line sections	
model of mosaic with failed edges	• estimate of point process intensity • estimate of mean cell area • fraction of failed edges	• number of edges of a crack • number of branching points of a crack
	• kinking angle • branching angle	• degree of branching • shape parameter of crack extension

Table 1: Statistical quantities used for characterization of random crack patterns.

forms of crack branching and the "zigzag" crack paths are not observed in this model, mainly because of two different reasons: First, branching is only possible in the fibre model by coalescence of two single cracks, whereas in reality, branching is obviously an additional mode of crack propagation. Second, the fibre process model describes crack propagation along a straight line, whereas in reality the underlying structure of the material seems to provide lines of preferred crack growth. However, the fibre process model provided a number of useful and easy to determine quantities.

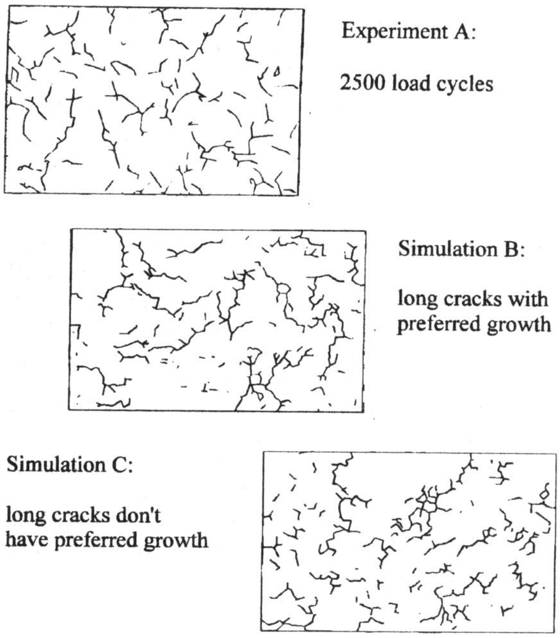
Referring to the physical background of the damage process, a more restricted crack path modelling [4] led to the "model of mosaic with failed edges". Potential crack paths were assumed to be along the edges of a random mosaic which is assumed to reflect weak lines in the material like grain boundaries, slip lines etc. Using methods of stochastic geometry, an estimation of the parameter of the mosaic is possible from an experimentally obtained crack pattern with help of the assumption that the crack pattern itself is an incomplete realization of a random mosaic. Typical quantities for this model describe the **underlying mosaic** (i.e. intensity of the mosaic-generating point process and the mean area of the cells of the mosaic), the **global damage** (i.e. the number of failed edges making up the crack pattern) as well as the **local damage** (i.e. geometric quantities of crack shape like branching or kinking angle or quantities describing the extension of a crack in different directions; see Table 1). An example is given in the next paragraph which illustrates the information content of the proposed quantities

COMPARING DIFFERENT CRACK PATTERNS

Crack patterns in the simulation were generated by load-dependent random failure criteria for segments at tips of existing cracks. Crack tip loading was modelled by a fracture mechanics loading parameter ***B*** with the effects of crack branching and interaction of neighbouring cracks taken into account [2, 5]. Using this parameter, it is possible to simulate the evolution of crack patterns. The evolution of the shape of individual cracks by branching and growth in the direction of maximum crack length

level of modelling	**mean values of characteristics**	**image A**	**image B**	**image C**
simple crack statistics	• number of cracks / mm^2	67.436	81.633	82.816
	• cumulative crack length / mm^2	10.493	11.036	10.999
	• length of a single crack	0.156	0.135	0.133
model of mosaic with failed edges	• point process intensity	567	2020	2027
	• number of crack segments	5.561	9.116	8.971
	• number of crack branches	0.772	1.246	1.229
	• degree of crack branching (evaluation of all cracks)	0.143	0.101	0.145
	• degree of crack branching (only branched cracks)	0.160	0.236	0.356

Table 2: Comparing different crack patterns (length unit is mm)



Experiment A:

2500 load cycles

Simulation B:

long cracks with preferred growth

Simulation C:

long cracks don't have preferred growth

Figure 1: Crack patterns from simulation and experiment

as well as the evolution of the crack pattern due to interaction effects depend on the crack growth model. Crack branching is governed by a characteristic length r_0, whose value determines the relative importance of crack propagation at crack end points compared to crack branching at kinks of an existing crack. Two different crack patterns generated by simulation are shown in Fig. 1 (B, C) together with one outcome of the experiment (A). The difference between B and C lies in a more pronounced probability of long cracks (high value of the loading variable ***B***) to grow in case B, whereas in case C, the growth probability increases linear with loading parameter ***B*** . In Table 2, numerical values are givern of some of the quantities listed in Table 1 .

THE INFORMATION CONTENT OF CHARACTERISTIC QUANTITIES

The quantities used in analysis of crack pattern have to serve two purposes: first they must reflect the visual impression of crack patterns (applicability of quantities) and second they have to discriminate between different patterns (discriminative power of quantities), even if they look very similar at first sight.

From Table 2, it can be seen that the quantities obtained by simple crack statistics cannot provide a distinction between the two different crack propagation models in B and C, which is in agreement with optical impression. Differences can be found, however, using statistical characteristics with better discriminative power such as the empirical distribution of crack lengths. Fig. 2 shows that B contains many short and some very long cracks, whereas crack lengths in C are more uniformly distributed. This reflects the different underlying growth models. The existence of many small and some few very long cracks means that growth of small cracks is a slow process and long cracks are generated mainly by coalescence. These cracks

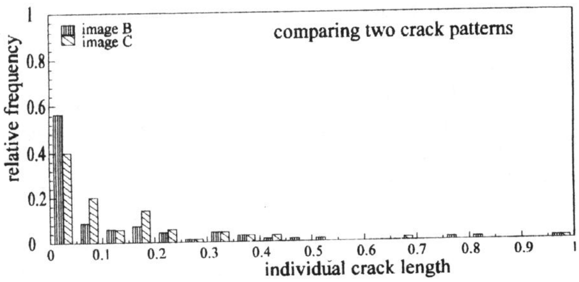


Figure 2: Histogram of crack lengths for B and C

then grow quickly either by propagation or further coalescence, mainly dominated by the neighbourhood of the crack, so that these two mechanisms therefore can not be separated by studying the behaviour of selected isolated cracks, as it is sometimes done in the evaluation of fatigue experiments.

Up to now, characteristic quantities were used to reflect and to complement visual impressions of different crack patterns. An essential question for the relevance of the used quantities as well as for the interpretation of the experiments is however the dependence of these quantities on variations in the underlying simulation model. Using different simulations with identical underlying microstructure (i.e. based on the same mosaic), it is possible to assess the significance of differences in the observed quantities and relate these to uncertainties in data acquisition for experimentally obtained patterns. Thus, randomness of microstructure and randomness in damage evolution can be separated in simulation, which is obviously impossible in experimental investigations. Detailed investigations show [6], that

- different realisations of a random mosaic of same intensity do not show a significant influence on the developing crack pattern.
- there is a certain impact of the initial (random) damage on the development of the crack patterns due to the existence of clusters with a tendency for coalescence.
- there is considerable variation in the realisation of random patterns which may overrule changes due to variation of parameters.
- quantities describing local characteristics of damage (crack shape, number of cracks) show larger variations than global quantities (cumulative crack length) due to locally dominating effects of interaction and coalescence.

Systematic variations of the various model parameters were performed to investigate the sensitivity of crack pattern characteristics. Some trends observed had not been anticipated. For example, the increase of failure probability at crack tips in relation to that at crack kinking points did not result in crack patterns with more elongated cracks and reduced branching, as expected. The reason for that was that inference on crack propagation from the behaviour of a single crack may be not quite correct because effects of interaction (especially shielding effects) may lead to opposite behaviour.

SUMMARY

This paper shows how fracture mechanics based stochastic models and simulations of random crack patterns can be used to derive methods for a statistical evaluation of simulated crack patterns and their comparison with experimentally obtained patterns in the case of thermal fatigue. The approach is useful for better understanding of the development of damage in case of an array of cracks and is also suitable for an assessment of different models for damage evolution.

Stochastic quantities are provide tools for a quantitative evaluation of random crack patterns. It is necessary to have specific characteristic quantities which reflect underlying mechanisms of crack propagation. On the other hand, random variations in the crack propagation behaviour, which may play an important role on a local scale (shape of an individual crack) turned out to be less important or even have contradictory effects on the global scale (crack pattern evolution). A typical example for this is the importance of crack interaction effects.

Stochastic simulation can also help estimate the amount of statistical scatter which is to be expected for quantities used in crack propagation and pattern development analysis. Interpretations can be found in greater detail in [4-6], where also the influence of uncertainties in data acquisition of the experimental patterns is addressed.

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