Experimental Characterization and Geometrical Modelling of Fatigue Fracture Profiles

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ABSTRACT

Based on experimental analysis of fatigue fracture profiles a model is presented which assumes stochastic crack events. The crack profile is characterized by log-normally distributed length elements and Gaussian distributed line angles. The model leads to simple relations between the length element, the angle and the height distributions. The meaning and necessity of filtering procedures in the evaluation of height distributions is explained. The experimental methods and the model results shown here can be related to the underlying microstructure.

KEYWORDS

Filtering; Fractography; Modelling; Stochastic fracture

INTRODUCTION

Studies on most fracture surfaces, irrespective of whether the crack proceeds in a stable or unstable manner, normally reveal a stochastic fracture process. Although this has been known for some time (e.g. Passoja and Psioda, 1981), only recently more systematic investigations (e.g. Karlsson et al., 1987; Karlsson and Wasén, 1988) performed on fatigue crack surfaces have offered firmer basis for quantitative characterizations. The stochastic fracture events imply that the evolving surfaces must be treated statistically by the aid of distributions. The irregular fracture surfaces make certain precautions necessary in the experimental recordings and invalidate the oversimplified geometrical modellings often made use of in the literature. Fatigue crack surfaces through a variety of microstructures have been quantitatively analyzed: single phase ferritic steels (Wasén et al., 1988a), pearlitic steels (Hamberg and Karlsson, 1988), ferritic-martensitic DP-steels (Wasén and Karlsson, 1988a), microduplex ferritic-austenitic stainless steels (Wasén et al., 1988b) and porous sintered steels (Bertilsson and Karlsson, 1987).

The purpose of this paper is to discuss some key factors in experimental recordings of fracture surfaces and to demonstrate suitable geometrical descriptors. Based on such information a realistic geometrical model is developed and analyzed. The model offers information on how the experimental strategy should be devised. A major result of the analysis is the presentation of precise relations between the different descriptors.

EXPERIMENTAL CHARACTERIZATION

In the experiments coordinates in the fracture profile are recorded by digitalization with a resolution of 0.5 μm on optical micrographs. Details are reported elsewhere (Wasén et al., 1987). The further evaluation does not demand this kind of data input since the profile coordinates can be measured by stereometry or by other means on the fracture surface itself. The resolution should be determined by the degree of detailed information needed (typically some per cent of the grain size). However, the evaluation techniques are general and applicable at any resolution level. A typical example of a fatigue fracture surface from a single-phase ferritic material is shown in fig. 1a (mean linear intercept grain size λ = 15μm). The irregular fracture has a typical transcrystalline character. An extended profile from the same material is shown in fig. 2, exhibiting height variations both on a fine and on a coarser size scale. The long wavelength variation is associated with height differences corresponding to several grains while the small scale height variations are of the order of the mean intercept grain size or less. Fourier analysis of fracture profiles typically reveals a continuous amplitude spectrum with smoothly decreasing amplitudes at diminishing wavelengths (Karlsson et al., 1987).

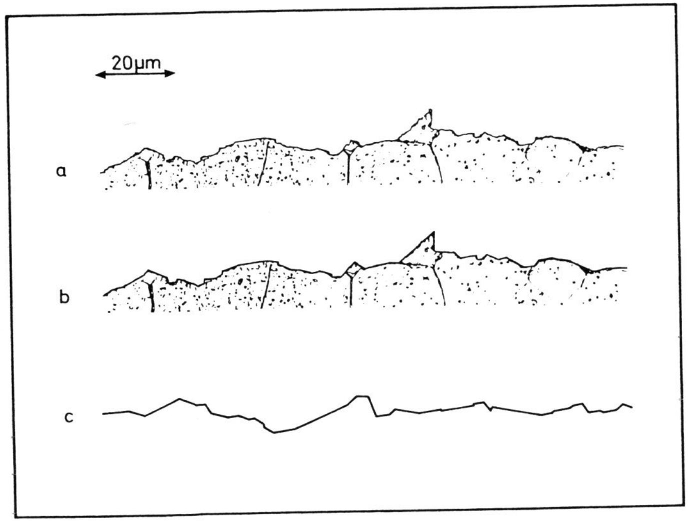

Fig. 1. a) Experimental crack profile from a ferritic steel.
b) Chord approximation of the profile in fig 1a.
c) Profile simulated using the process shown in fig. 3.

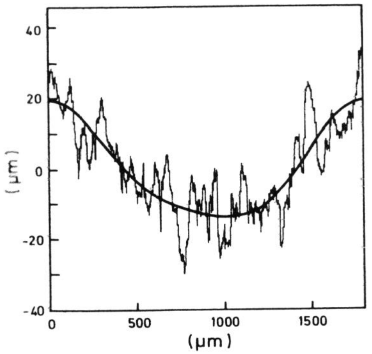

Fig. 2. Extended fracture profile material as in fig. 1a.

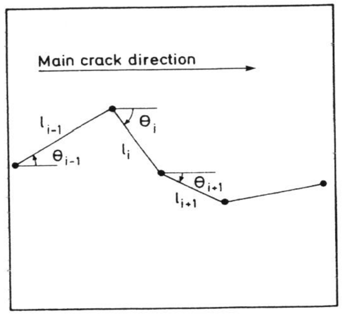

Fig. 3. Simulation process.

Observations of a large number of fatigue fracture profiles from ferritic steels studied have shown that the real profiles with good precision can be approximated by straight line segments (fig. 1b; cf. fig. 1a). Though strict geometrical criteria for these adjustments are still to be found, the manual procedure itself is not problematic. Analysis of fracture profiles in ferritic steels have shown a log-normal size distribution of the linear elements (Wasén et al., 1988a; Karlsson and Wasén, 1988). The (arithmetic) mean line element size $\bar{l}$ is linearly dependent on the mean intercept grain size ($\bar{l}$ is typically 20-30% of λ), and the standard deviation is 0.6 to 0.7 times the mean value coinciding with that of the log-normally distributed linear grain intercepts (Karlsson and Wasén, 1988).

In addition to the size distribution of the line elements the profile can be characterized by the length weighted distribution of the orientation angles θ (fig. 3). Measurements on fatigue fracture profiles in one- and two-phase materials have shown that the angle distributions can be represented fairly well by truncated Gaussian distributions (Karlsson and Wasén, 1988).

The third main descriptor is offered by the distribution of heights of the line profile. It is clear from fig. 2 that, because of the waviness of the profile, a true averaging of the height distribution hardly could be expected, considering that the total length of digitalization in practice seldom exceeds 5 to 10 mm.

MODELLING

The model used is based on experimental analysis of fracture surfaces in ferritic steels. A successful model must fulfill the following experimentally found demands (Karlsson et al., 1987; Wasén and Karlsson, 1988b):

1. It must regenerate characteristic geometrical variables of the fracture surface like the height distribution, the Fourier spectrum and the fractal properties.
2. The angle distribution should be independent of the height position of the crack tip.
3. The process must be non-repetitive.

These requirements have been shown to be fulfilled (Karlsson et al., 1987; Wasén and Karlsson, 1988b) by a successive stepping process (fig. 3) where each step is chosen according to a stochastic choice of chord lengths and angles from prescribed distributions. The length elements were assumed log-normally distributed with standard deviation 0.6 times the arithmetic mean value, while the length-weighted angle distribution were chosen as Gaussian distributions truncated at ±90° with selectable standard deviation $\bar{\theta}_L$. These distributions were used in the model analysis to conform with the experimental findings but, of course, any distributions could be employed.

In the computer evaluation of this model the total number of line elements analyzed for each set-up of parameter values was chosen to ensure good averaging. In general this corresponds to total lengths larger than what is achievable in most experiments. The simulated curves were then analyzed regarding the height distribution of the length element chain and the spectral properties as expressed in the Fourier spectrum and the fractal curve; the latter results are reported elsewhere (Wasén and Karlsson, 1988b). An indication of the capability of the stochastic stepping model is qualitatively shown in fig. 1c which recreates essential characteristics of the fracture profile in fig. 1a.

CHOICE OF CRACK PATH

The predictive power of the model can be used to study possible paths of a running crack. A typical example simulating the experimental conditions in fig. 2 is shown in fig. 4. It is seen that the crack macroscopically is rather close to an ideal mode I geometry, whereas the crack on a micro-scale can deviate considerably perpendicular to the main fracture plane (cf. the waviness of the experimental fracture profile in fig. 2). In order to get a statistical measure of the possibility of deviation from the main fracture plane several runs were performed with identical starting points. From a multitude of such runs the standard deviation ($\pm\sigma_d$) of the crack tip position as referred to the main fracture plane could be evaluated for different crack lengths a (fig. 4). Selecting $\bar{\theta}_L = 35^{\circ}$ with arithmetic means $\bar{l}$ of the crack element lengths varying from 5 to 20 μm (typical for ferritic steels with mean intercept grain sizes in the interval 15 to 80 μm) gave the result in fig. 5 for total crack lengths extended up to 20 mm. Linear regression of the data in fig. 5 leads to the following equation:

$$\sigma_d = k_1 \cdot (\bar{l}\cdot a)^{1/2} \qquad (1)$$

Similar analysis for various widths of the angular distribution resulted in a simple dependence of k_1 on $\bar{\theta}_L$ (fig. 6):

$$k_1 = 1.17\,\sin(\bar{\theta}_L) \qquad (2)$$

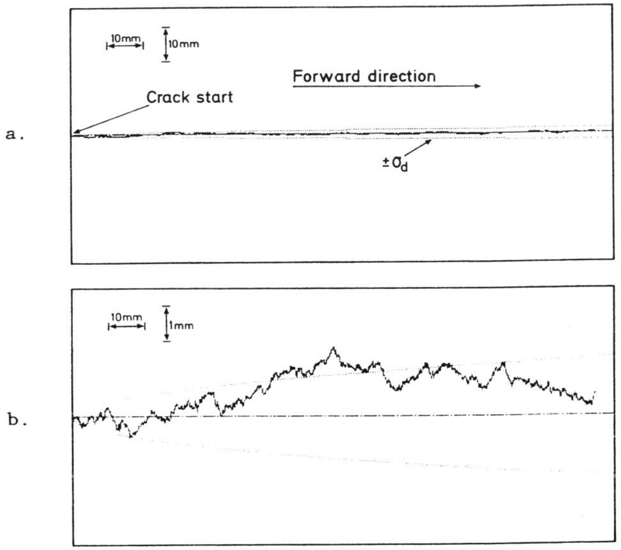

Fig. 4. Simulations of crack profiles, cf. main text.

From eqs. (1) and (2) there follows the following parabolic relation:

$$\sigma_d = 1.17\,\sin(\bar{\theta}_L) \cdot (\bar{l}\cdot a)^{1/2} \qquad (3)$$

It is evident from eq. (3) that the "vertical deviation" of the moving crack increases with increased angular deviations and increased sizes of the length elements. Fig. 4 can, if desired, be generalized by scaling the vertical axis in units of $(\sin(\bar{\theta}_L)\cdot\bar{l}^{1/2})$.

It is important to realize that any single profile can proceed along a limitless number of different paths in the actual "crack propagation band" as defined by the crack initiation site and eq. (3).

FILTERING

The presence of all components in the Fourier spectrum indicates that no true averaging of the height distribution can be reached in measurements on limited lengths of the profile line. Furthermore, it means that the profile normally exhibits a longwaved irregularity as indicated in fig. 4b. A method to suppress the non-averaged information is to subtract the longest wavelengths by filtering in a Fourier transformation procedure (Wasén et al., 1987). The choice of cut-off wavelength in the filtering is arbitrary and no "natural" value exists (Wasén et al., 1987). In the

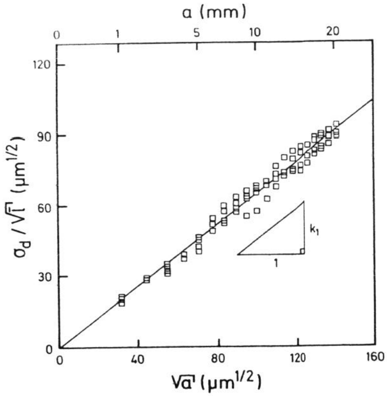

Fig. 5. Simulation of sideways deviation of moving cracks, cf. main text.

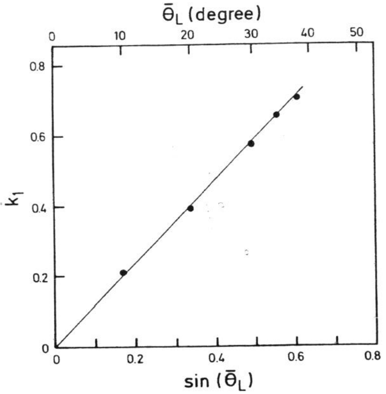

Fig. 6. Slope k_1 in fig. 5 for different $\bar{\theta}_L$.

analysis performed below a cut-off wavelength at 200 times the mean line element length (corresponding to approximately 50 grains) was used. The analysis of the filtered profile is then based on a new reference line identified with the filtered-away long wavelength components. In practice the total length of the measured profile should correspond to least 500 grains to ensure true averaging. Previous studies (Wasén et al., 1987) indicate that the height distribution is narrowed at diminished cut-off wavelengths, while the angular distribution is rather unaffected. Further details on the filtering technique have been discussed by Wasén et al. (1987).

RELATIONS BETWEEN DIFFERENT GEOMETRICAL DESCRIPTORS

In order to find relations between the different geometrical descriptors for a given profile a detailed analysis of the linear step model was performed. As above a stochastic choice of angles from truncated (±90°) Gaussian angle distributions and length elements from log-normal distributions was made. The final analysis was performed on filtered profiles. The number of chords in each simulation was approximately 2000 securing acceptable averaging.

With an angular distribution like that of ferritic alloys ($\bar{\theta}_L = 35^\circ$) (Wasén et al., 1988a) and a variation of the arithmetic mean step length $\bar{l}$ between 2 and 50 µm the analysis gave a proportionality between the width of the height distribution and $\bar{l}$ (fig. 7)

$$\bar{H} = k_2 \cdot \bar{l} \tag{4}$$

where $\bar{H}$ is the standard deviation of the Gaussian shaped height distribution. Experimental data taken from ferritic structures with mean intercept grain sizes between 15 and 82 µm nicely fit into the theoretical results (fig. 7).

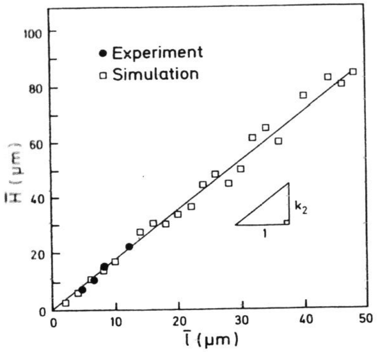

Fig. 7. $\bar{H}$ vs. $\bar{l}$ for $\bar{\theta}_L = 35^\circ$. Simulation.

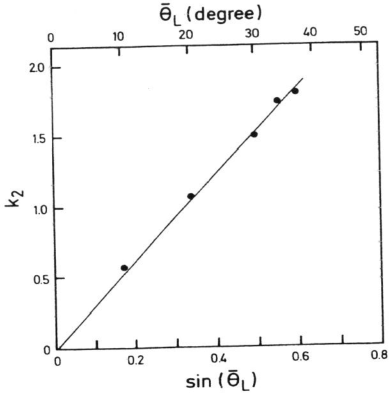

Fig. 8. Slope k_2 in fig. 7 for different $\bar{\theta}_L$.

Evaluation of the model for different $\bar{\theta}_L$-values (fig. 8) showed that the proportionality factor k_2 in eq. (4) is simply related to $\bar{\theta}_L$:

$$k_2 = 3.05 \sin(\bar{\theta}_L) \tag{5}$$

A combination of eqs. (4) and (5) results in the following expression for the mean standard deviation of height $\bar{H}$:

$$\bar{H} = 3.05 \sin(\bar{\theta}_L) \cdot \bar{l} \tag{6}$$

In this relation $\bar{l}$ indicates the size scale whereas sin ($\bar{\theta}_L$) is associated with the "sideways" movement of the crack elements. The proportionality factor in eq. (6) is estimated to have less errors than a few per cent. As indicated above the proportionality factor should decrease with decreasing cut-off wavelength. A quantitative analysis of such a dependence would need very voluminous calculations on a large number of profiles created by different combinations of $\bar{l}$ and $\bar{\theta}_L$. This prevented such an analysis to be performed. However, limited experimental checks made earlier (Wasén et al., 1987) indicate a typical decrease of $\bar{H}$ with 10 % upon reduction of the cut-off wavelength by a factor 2 at wavelengths corresponding to approximately 50 grains.

CONCLUDING REMARKS

Experimental data from both one- and two-phase microstructure have shown that the mean standard deviation of height $\bar{H}$ can be used as a determining parameter for the crack closure (Karlsson and Wasén, 1988). Although the model above is mainly applicable to single phase materials, it is reasonable to expect that $\bar{H}$ should be determined by both the angle and crack element size distributions in a similar manner also for two-phase materials. The experimental information available so far mostly concerns fatigue cracks, but data from unstable crack growth situations indicate stochastic crack events also in this case (cf. Sigl and Exner, 1987). Therefore, the techniques developed here are judged to have fairly general applicability.

The types of distributions needed to describe the fracture surfaces are often rather simple and can be characterized by means and standard deviations. The following important conclusions may be drawn from the present investigation:

1. Profiles can with good accuracy be approximated with a chain of straight length elements.
2. The mean standard deviation of height $\bar{H}$ is linearly proportional to the arithmetic mean $\bar{l}$ of the approximating chords and $\sin(\bar{\theta}_L)$, where $\bar{\theta}_L$ is the standard deviation of the length weighted angle distribution.
3. Assessment of true averaging requires a filtering procedure to be performed in the experimental recordings. The cut-off wavelength used in the filtering is a matter of judgement because of the stochastic character of the fracture process.
4. The stochastic model analyzed using prescribed angle and length element distributions is very powerful in predicting the essential geometrical characteristics of the crack surface.

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