FATIGUE MICROCRACK DISTRIBUTIONS AND CORRELATION WITH FATIGUE LIVES DISPERSION

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In order to investigate the relationship between microcrack size statistics and scatter of fatigue lives, surface cracks of six smooth cylindrical specimens, tested under rotating bending fatigue at the same stress level, were measured and counted. The analysis of crack size distributions show that neither the Weibull distributions of crack lengths nor the statistics of extreme cracks are significantly dependent on fatigue lives. Microcrack density and total crack length per unit area resulted as linearly correlated with cycles to failure of the tested specimens.

INTRODUCTION

It is well known that surface microcrack density can be taken as an indicator of fatigue damage accumulation and several authors studied the evolution of surface microcracking under fatigue loads by the observations of small specimen areas. It has been found that microcrack density and the total number of cracks increases during fatigue life (Bomas et al. (1), IIda (2) and Goto (3)) , the total length of cracks per unit area being proposed as damage indicator (2). During fatigue life there occurs a transition of crack size distributions, fitted by the three parameter Weibull equation, toward higher lengths with characteristic shape changes, depending on material and stress level (3). Studying the evolution of the same type of probability density curve, Hyspecky and Strnadel (4) proposed a criterion for the transition from short crack growth range to long crack one. Taylor (5), from data of ref. (3), then proposed the so called P-a (probability of propagation against crack length) plots aiming to describe the statistics of fatigue behaviour.

In order to investigate practical applications of the above mentioned methods, the authors studied the scatter of crack size distribution properties by the examination, via NDT techniques, of the surface cracking of six specimens, made of heat treated carbon steel.

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The tested material, whose S-N diagram was already discussed by the authors in (6), has tensile and fatigue behaviour very similar to those of the steel studied by Goto, thus allowing a comparison between ref. (3) and present results.

The goal of the paper is to study the correlation between the fatigue life of each specimen and the characteristics of its final surface crack density distribution, searching for the most significant parameter.

EXPERIMENTS

The material tested was heat treated 0.43% carbon steel, the chemical composition (wt %) being 0.43 C, 0.15 Si, 0.64 Mn, 0.01 P and 0.006 S. The mechanical properties were 715 MPa yield stress, 887 MPa tensile strength, 550 MPa cyclic yield stress and 430 MPa rotating bending fatigue limit.

The cylindrical specimens, with $\Phi = 6.7$ mm diameter and gauge length of 48 mm, were finished by longitudinal hand polishing with 1000 grade emery paper. The rotating bending fatigue tests were performed at 33.3 Hz on uniform bending type machine with a capacity of 30 Nm.

The observations of crack lengths were made, after fatigue tests, on six specimens tested at 550 MPa stress level, whose fatigue lives are reported in Table 1.

TABLE 1 - Fatigue lives of the examined specimens.

specimen	A	B	C	D	E	F
cycles to failure	35000	40000	47000	51000	71000	91000

The measurements, along the circumferential direction, of the crack length on the different specimens were made via microphotos of the entire surface of the test pieces. Before taking pictures, the broken specimens were subjected to wet magnetic particle application to easily detect the surface microcracks. With a magnification of X30, a number of 48 photographs was needed to represent the entire surface with sharply focused images. It was assumed, on the basis of calibration measurements on plastic replicas, to take into account in the analysis only magnetic particle indications corresponding to surface flaws longer than 0.05 mm.

RESULTS AND DISCUSSION

The cracks found on the different specimens were then measured and recorded in order to investigate the relationships among some properties of crack distributions and fatigue lives.

Crack length distributions. Fig. 1 shows the histograms of crack dimensions, in the range 0.050 ÷1.017 mm, of the examined specimens. According to the transition of crack size distributions during fatigue life observed in (3) and (4), we expected a shift toward higher dimensions of crack length frequency distributions with increasing cycles to failure. However in spite of the wide endurance spread and of the distinctive surface patterns, there are no considerable differences among the histograms, except at the 0.072 mm class where specimens A and B have relative frequency higher than the other test pieces.

Because of the negligible differences of tensile properties and S-N diagram of the tested material from those of the material studied in (3), it was possible to compare histograms with the Weibull distribution of crack sizes found by Goto at 550 Mpa stress level: it resulted that data pertaining to the different specimens are not significantly distinct from the crack length distribution found in (3).

Statistics of extremes. Since fatigue behaviour is related to the growth scatter of major cracks (after Goto (7)) and thus it seems connected to the behaviour of extreme members of defects (after Murakami (8)) and cracks (5) populations, we analysed crack data in terms of extreme values, considering only the local maximum size found on each photo. This procedure allows to focus the attention on the tails of cracks length distributions otherwise underestimated, because of their small influence on the shape of frequency curves. The so obtained samples, plotted on extreme value probability paper in fig. 2, are not significantly different. The analysis of the whole data (fig. 3.a) by Type I Extreme Value cumulative frequency distribution:

$$F(y) = \exp\left[-\exp\left(-(y-\mu)/\sigma\right)\right] \tag{1}$$

reveals that cracks longer than 1.5 mm belong to a distribution completely different from that of short ones (fig. 3.b). This suggests the presence, in this size range, of different growth mechanisms, such as the coalescence of small cracks (7), whose effect can be underestimated observing small surface areas .

Crack Density and Total Crack Length. In table 2 are reported the two parameters mostly referenced as fatigue damage indicators: the crack density and the total crack length per unit area, calculated respectively as total number and total length of measured cracks ratioed to the specimen surface area (≈ 1000 mm^2).

Both the two parameters firstly describe the difference among surface patterns: a great number of short and long cracks quite uniformly distributed for specimen A (1280 fractures) against some few cracks sometimes gathered around longer ones on specimen F (340 cracks found).

The relationships of crack density and total length per unit area against the fatigue life (fig. 4.a and 4.b respectively) are both linear, the ANOVA supporting 95% confidence tests. In spite of the highest scatter of length data, it has to be noted that the neglect of microcracks shorter than 0.05 mm has much more influence on density measure than on evaluation of length per unit area.

Table 2 - Crack density and crack length per unit area of the examined specimens.

specimen	crack density [1/mm^2]	crack length per unit area [mm/mm^2]
A	1.2696	0.1690
B	1.4844	0.2142
C	0.8470	0.1511
D	0.9584	0.1941
E	0.7755	0.1544
F	0.3380	0.0785

CONCLUSIONS

The analysis on surface crack length distributions of six specimens of a heat treated medium carbon steel, tested at the same stress level, show that neither the frequency distributions of crack dimensions nor the extreme value distributions of largest cracks can be significantly correlated with fatigue lives.

Nevertheless the crack density and the total crack length per unit surface, that are indicated in most references as damage accumulation parameters, have a strong linear dependence on fatigue endurance.

Aknowledgement. Research has been made by MPI 60%-92 grant of P. Clerici.

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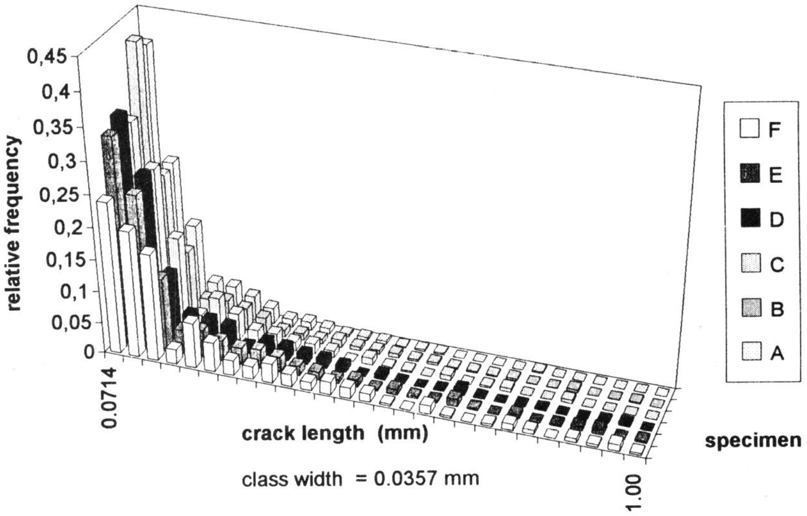

Fig. 1. Histograms of the crack lengths of the tested specimens.

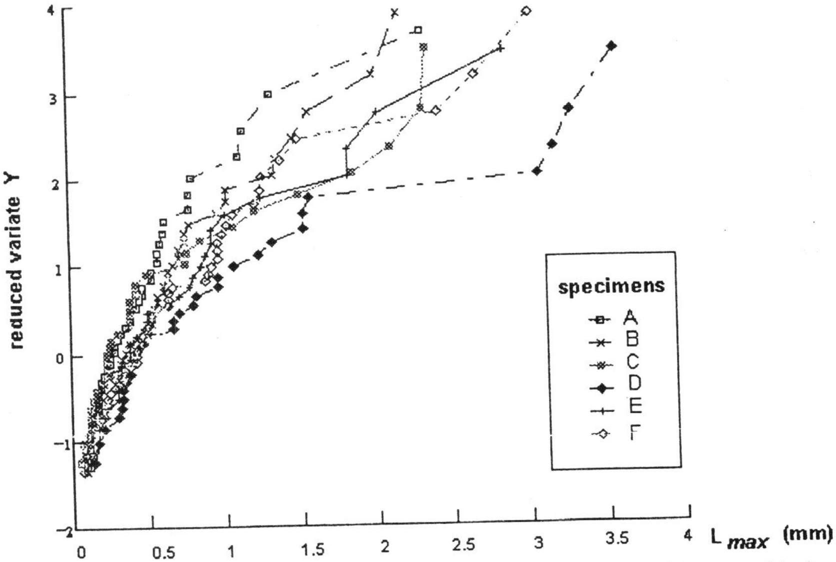

Fig. 2. Extreme Value type I probability paper of maximum lengths, considering separately the different specimens.

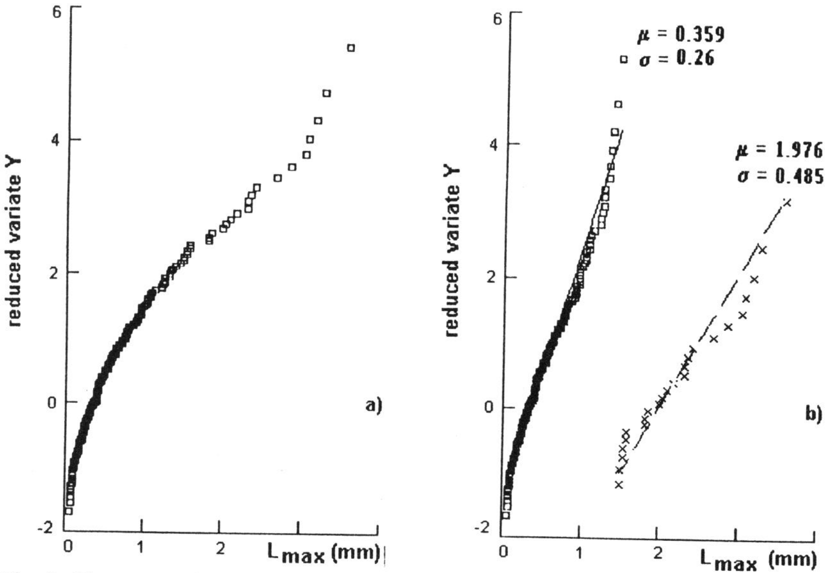

Fig. 3. Extreme Value type I probability paper of maximum lengths: a) the whole data; b) the separation into two different populations.

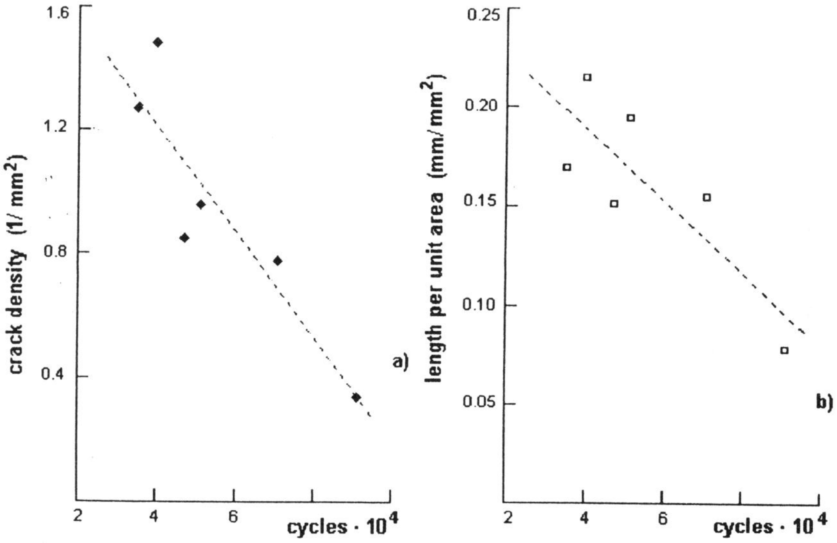

Fig. 4. Linear relationships of damage parameters against fatigue lives: a) crack density; b) total crack length per unit area.