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BEHAVIOUR OF FATIGUE SHORT CRACKS IN A MEDIUM CARBON STEEL SUBJECTED TO REVERSED TORSION

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The results of investigations into fatigue short cracks behaviour in a medium carbon steel under reversed torsional loading are presented. Characteristic features of surface crack initiation and crack growth were established on the basis of replication method and electron-optical observations. The plots of crack length, crack growth rate, crack population and crack length distribution versus cycle ratio have been hereby analysed. Relations between crack growth and microstructural features in the test pieces under investigations were enhanced.

1. Introduction

For last two decades short fatigue cracks behaviour have been intensely investigated in aspect of improving the fatigue resistance of metal and more precise estimation of the lifetime of engineering structures. Considering the limitation of short crack description by conventional formulas of fracture mechanics and taking into account specific behaviour of the cracks it is necessary to define the regime of short cracks growth. This term can be defined either by stress range needs for crack growth or selecting the crack length range. In this context Miller (1993) distinguishes two zones within the range of short cracks. Microstructurally short cracks zone includes the cracks of length less or comparable with grain sizes. In this case microstructural fracture mechanics is applied to describe the shear crack propagation of the stage I. When the cracks extend a grain size and reach the length compared with ten multiplicities of grains diameter physically small cracks regime is considered and elastoplastic fracture mechanics is required to describe the stage II cracks. Observations of short cracks behaviour indicate strong influence of microstructure of a metal and decreasing of crack growth rate in the range of crack length below a threshold value.

Miller introduces two threshold values to fatigue crack propagation. The first threshold is related to the metal microstructure and the second one is mechanically-based value. Threshold stress intensity factor of linear fracture mechanics is refered to mechanically-based threshold and differs short and long crack ranges. The results of researches into discussed problem allowed setting the upper limit of short crack range at $0.2 \div 0.5$ mm for constructional normalized carbon steels.

Short fatigue cracks have been the subject of numerous researches and state of the problem has been widely presented by Miller and de los Rios (1986), (1992) and in a special issue of the journal [25]. These publications contain the papers presented on the conferences organized in Sheffield (UK) and devoted to the short cracks problem generally. The principles and basic formulae for short crack growth rate established by numerous authors in 1980-1985 have been gathered in by Kocańda and Kocańda (1989). A continuously increasing number of publications and conferences devoted to the short crack problem prove the weigth of considered question. Therefore, a limited number of the papers comprised only 1994-1995 will be discussed here.

Short crack growth was investigated in notched test pieces made of NiCrMo steel (cf Ahmad et al. (1994a,b)) considering the shape and plasticity of the notch. Fatigue microcracks distribution described by the Weibull formula and correlation with fatigue lives dispertion was discussed by Beretta and Clerici (1994). Prediction of fatigue lifetime of a normalized carbon steel has included short and long crack growth regime (cf Bomas et al. (1994)). Statistical investigation of the behaviour of small cracks in a carbon steel (0.21% C) and the influence of ferrite grain sizes on fatigue lifetime was the subject of work by Goto (1994). On the basis of linear fracture mechanics a model for short fatigue crack growth has been proposed by Zhu (1994). Similar model for small and long cracks was discussed by Nisitani and Oda (1994). Crack growth closure behaviour and effective stress intensity factors for short fatigue cracks were analysed by Pang and Song (1994). Short crack opening behaviour was considered while the description of crack growth in notched specimens was proposed by Khazhinsky (1994). Fatigue limit of notched samples was predicted taking into account propagating and non-propagating short cracks (cf Kewei et al. (1995)). Relative changes in values of stress intensity factors have been also calculated in the aforementioned work. Possibilities and limitations of a turbine rotor operation were analysed by Grkovic and Nedeljkovic (1995) in aspect of short cracks growth. Short crack evaluation process was computer simulated from the point of view of influence the grain sizes on crack initiation and crack coalescence process (cf Hong et al. (1995)). Influence of the local microstructure of metal on short crack propagation was analysed by Edwards and Xu-Dong (1995). Closure behaviour of small corner cracks and their propagation in a ferritic-pearlitic steel (0.25% C, 1.1% Mn) were investigated by Craig et al. (1995).

The presented papers prove the developments of the study of short cracks in the world in the past two years both in conceptual and experimental aspects.

In our country the researches into short crack behaviour in steels have been commenced in 1992 and conducted by the authors. Short crack growth behaviour, crack density and crack length distribution were investigated in laser hardened samples (cf Natkaniec et al. (1994a,b)) and in shot peened ones (cf Kocańda and Kocańda (1995); Natkaniec et al. (1995)) made of a medium carbon steel. The results of the researches allowed us to establish characteristic features of short cracks and verify the method for probabilistic crack growth description and fatigue life prediction, which have been proposed by the authors (cf Kocańda et al. (1995a,b)). A part of the results obtained by the authors and related to short cracks behaviour in normalized 45 steel is presented here.

2. Experimental procedure

Normalized medium carbon steel 45 of the composition (wt %): 0.48 C, 0.66 Mn, 0.24 Si, 0.02 P, 0.019 S, 0.25 Cu, 0.24 Cr, 0.028 Al, 0.03 Mo, remainder ferrite was used for the fatigue tests. Mechanical properties of the steel were as follows: yield stress = 425 MPa, ultimate tensile stress = 690 MPa, elongation = 18%, reduction of area = 40%. The specimens of geometry and dimensions given in Fig.1 were finely polished first, by successively finer grades of emery papers and then by a diamond paste to 10 μm or 1 μm. Using the Vickers hardness penetrator the marks of pyramides were made on sample surfaces to select the same places on all replicas for examination of the crack growth. Prior to fatigue tests the sample gauges were ligthly etched in 0.5% nital and 4% picric acid to reveal microstructural barriers for crack advance.

Fatigue tests were carried out under load controlled reversed torsion at the frequency of 5 Hz. Surface shear stress range in the minimum cross-section was calculated from the cyclic stress-strain curve taking into account the Nadai relationship for elasto-plastic range. Surface crack growth was monitored by

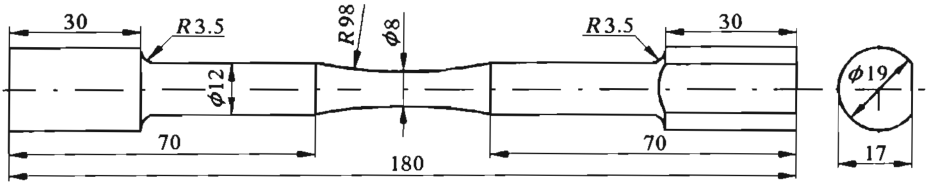

Fig. 1. Geometry of the specimen (dimensions in mm)

taking plastic replicas from the specimen surface at given intervals of load cycles N_i. Crack length and crack population in an unitary area were estimated with the help of an optical microscope equipped with a computer image analysis system. The spots of crack initiation and characteristic features of surface short crack growth were established on the basis of further observations of the replicas made using a transmission electron microscope (TEM). For the TEM microobservations the replicas were shadowed by platinum.

3. Results

Short cracks in normalized carbon steels, steel 45 included, are initiated and propagate practically in ferrite grains. Slip bands are usually the source of crack initiation. Direction of crack growth under reversed torsion is determined by the planes of the highest shear stresses, although it is not a rule. A network of the surface cracks nearly perpendicular to each other is originated with the specimen-axis-orientated cracks prevailing. This is affected by ferrite bands originated while rolling bars. Examinations indicate that microcracks were temporarily arrested at the ferrite grains boundaries and most often completely arrested at the pearlite grains boundaries. Examples of crack initiation and propagation have been shown on the micrographs in Fig.2 and Fig.3. Horizontal edges of the micrographs coincide with sample axis. The images have been derived from the sample surfaces examined at $\tau_a = 232\,\text{MPa}$ after $4 \cdot 10^3$ cycles (Fig.2a,b,c,) and 10^4 cycles (Fig.2d). Figure 2a shows an individual microcrack grown in the slip plane inside the ferrite grain. A system of parallel cracks originated from single slip bands is visible in Fig.2b. Three microcracks perpendicular to each other are shown in Fig.2c. The strongly developed slip bands even with slip lines visible are to be seen in Fig.2d. There is the site of crack initiation in the slip band bordered with a pearlite grain boundary. Parallel cracks shown in Fig.3a and Fig.3b have become visible

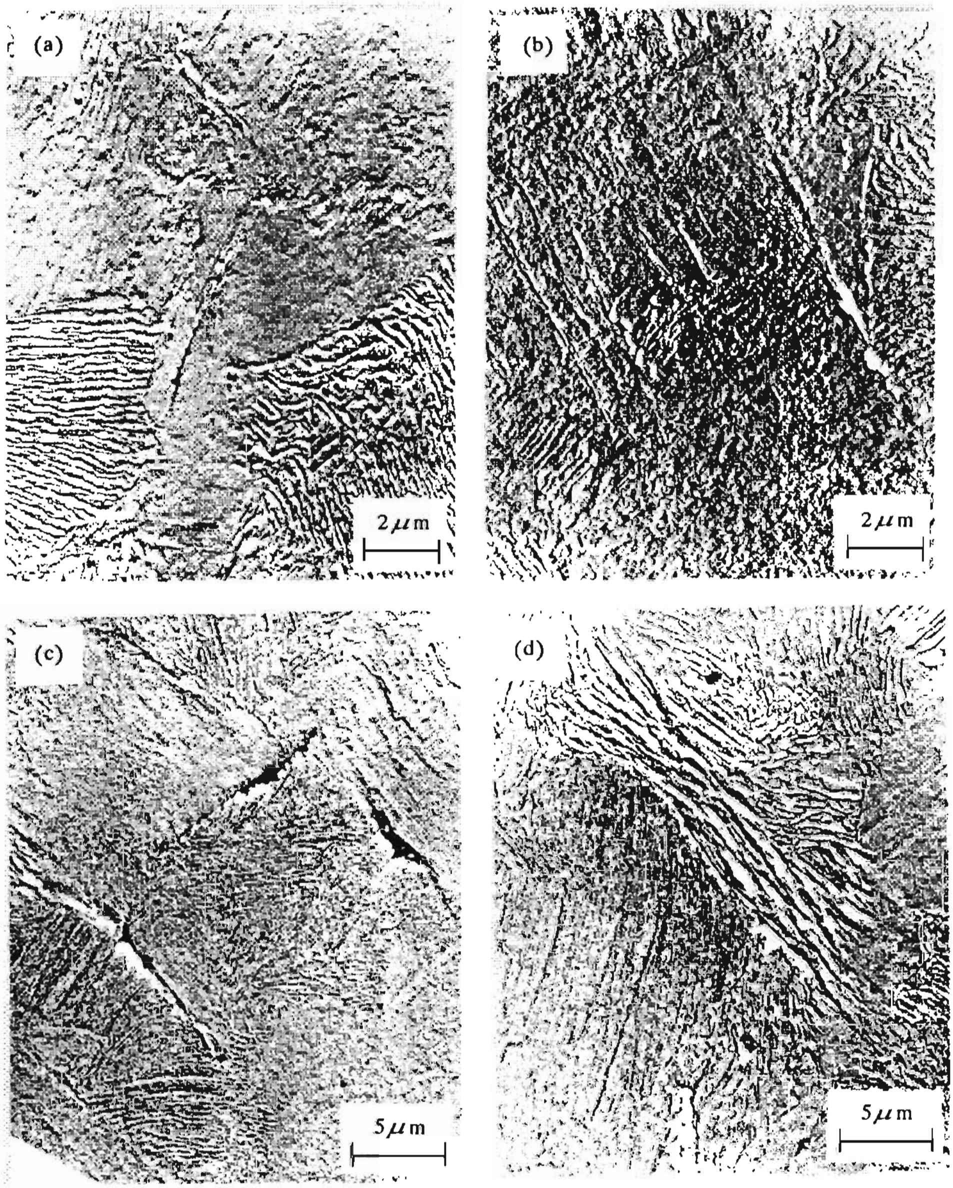

Fig. 2. Different systems of surface short cracks

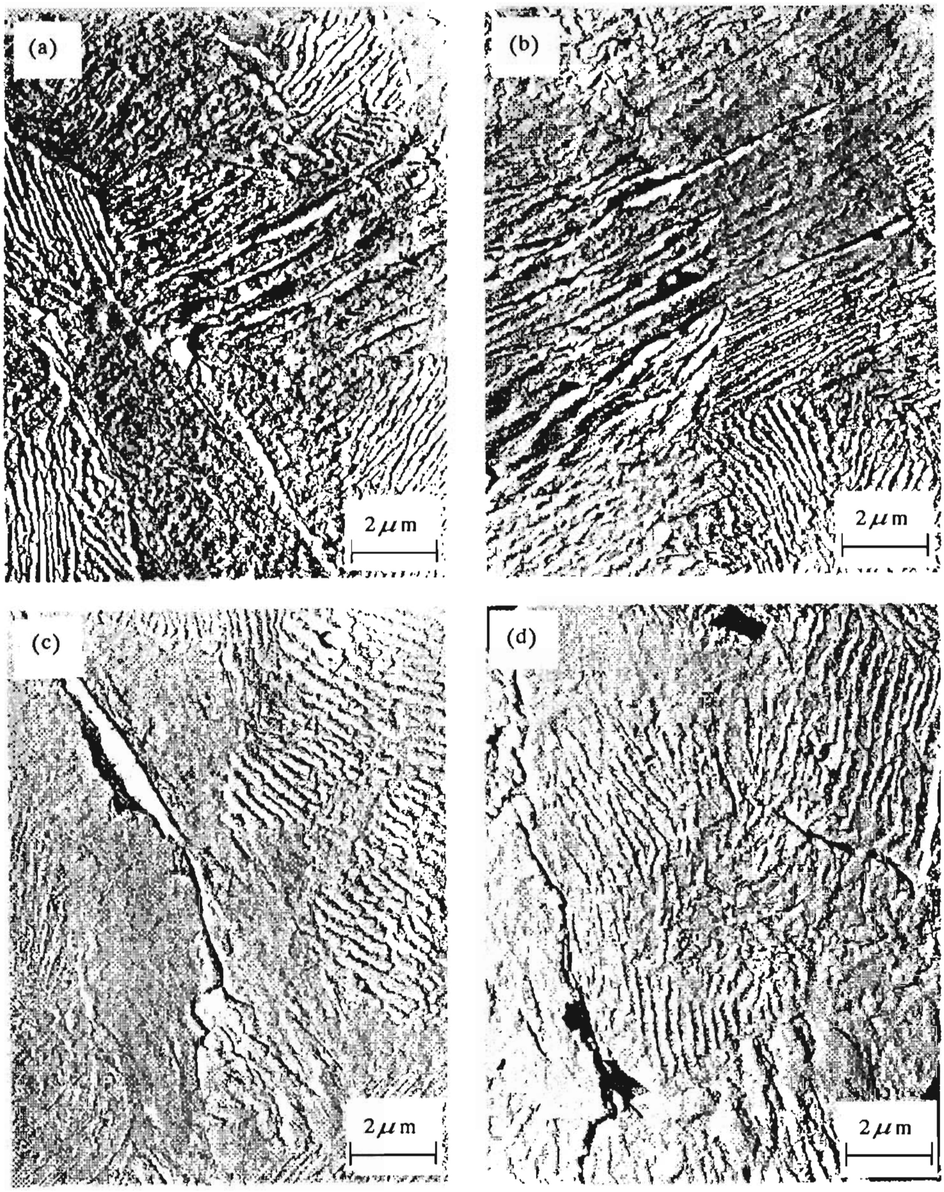

Fig. 3. Different systems of surface short cracks

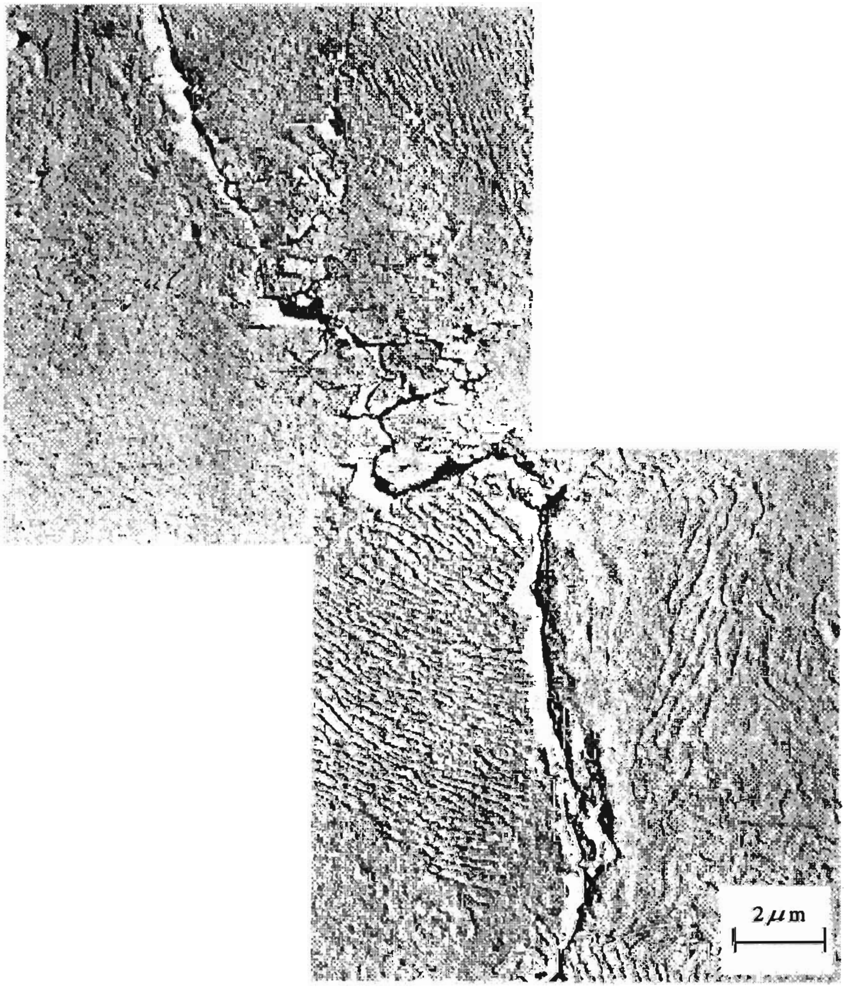

Fig. 4. Path of a surface crack running throught a ferrite grain (upper image) and along a pearlite grain boundary (lower image)

in slip bands as well, with well-marked extrusions. Singular crack seemed in Fig.3c has originated from coalescence of four microcracks. Very rare circumstances of crack initiation (one per a hundred) has been found in the pearlite grain given in Fig.3d (weakly visible bands of cementite inside the grain). A branched microcrack (Fig.4) altered direction of the propagation at pearlite grain boundary and enlarged on along this boundary.

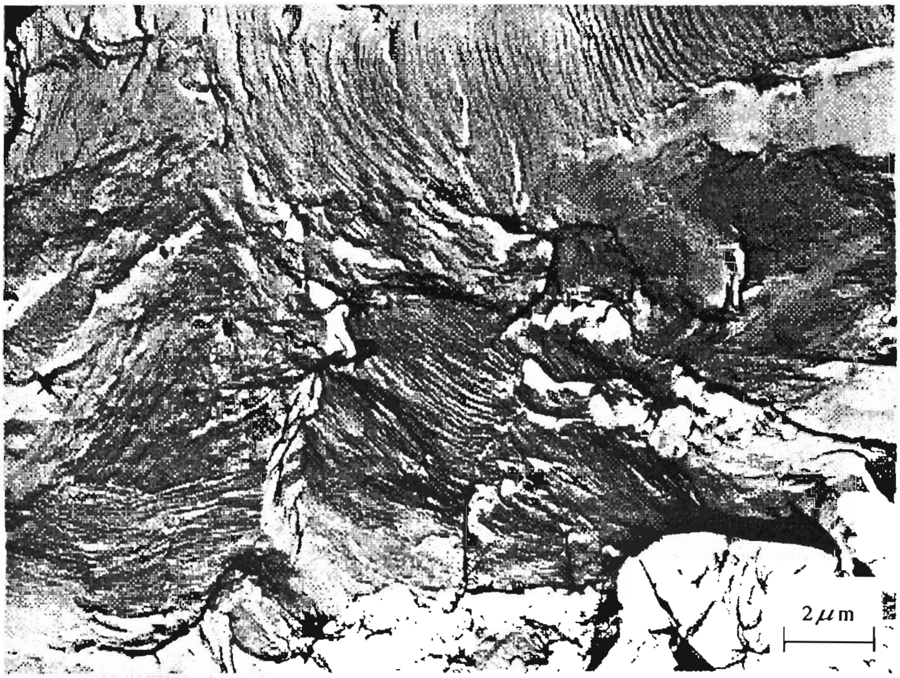

Fig. 5. Microregions with the systems of fatigue striations orientated in different way seemed on surface fracture (a TEM micrograph)

From the presented micrographs the evidence energes that the cracks initiate and grow in ferrite grains essentially and temporarily are arrested at the grains boundaries or blocked by previously initiated cracks. Various paths of surface short cracks propagation are attributed to local changes in the growth direction of cracks depth. The evidence of this fact is reflected on the TEM micrograph of the fracture surface shown in Fig.5. Certain systems of variously orientated plastic fatigue striations seemed there in a small area of fracture surface (15μm × 15μm) indicate four directions of crack depth growth.

Characteristic behaviour of short crack growth have been reflected in diagrams of crack length depending on a number of cycles (Fig.6a, Fig.7a) or

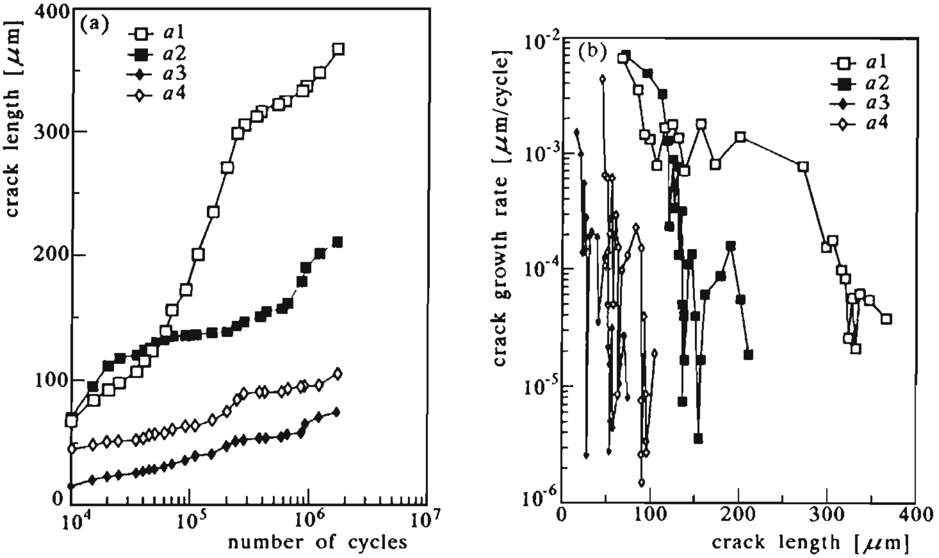

Fig. 6. Plots of crack length against number of cycles (a) and crack growth rate against crack length (b) drawn for four cracks developed in specimen tested at torsional stress $\tau_a = 170\,\mathrm{MPa}$

cycles ratio N_i/N_f (Fig.7b); crack growth rate versus crack length (Fig.6b, Fig.7c) or cycles ratio (Fig.7d) (N_i – number of current cycles, N_f – number of cycles to failure). The diagrams in Fig.6 have been drawn for the specimen tested at the shear stress amplitude $\tau_a = 170\,\mathrm{MPa}$ close to the value of torsional fatigue limit $\tau_{fl} = 168\,\mathrm{MPa}$. Four curves signed as $a1$, $a2$, $a3$, $a4$ represent experimental results recorded for four individual cracks, which have developed in a vicinity of dominant crack in the specimen. Small increments of crack growth (Fig.6a) or successively appearing sharp increases and decreases in crack growth rate (Fig.6b) result from temporary crack arrest at ferrite grains boundaries. Average size of ferrite grains was $15 \div 20\,\mu\mathrm{m}$. At pearlite grains boundaries the cracks were blocked for a time interval depending on the applied stress range (Fig.6b). The affectation by microstructure of a metal is confirmed as well.

Similar diagrams were produced for the specimens tested under different shear stress amplitudes (Fig.7). The curves in Fig.6 and Fig.7 refered to $\tau_a = 170\,\mathrm{MPa}$ illustrate the development of the longest crack found in the sample. In the test pieces fatigued under $\tau_a = 164\,\mathrm{MPa}$, slightly below the fatigue limit, generally, the cracks do not exceed $100\,\mu\mathrm{m}$ in length and they enlarge significantly slow in whole test time. For those cracks the curves of

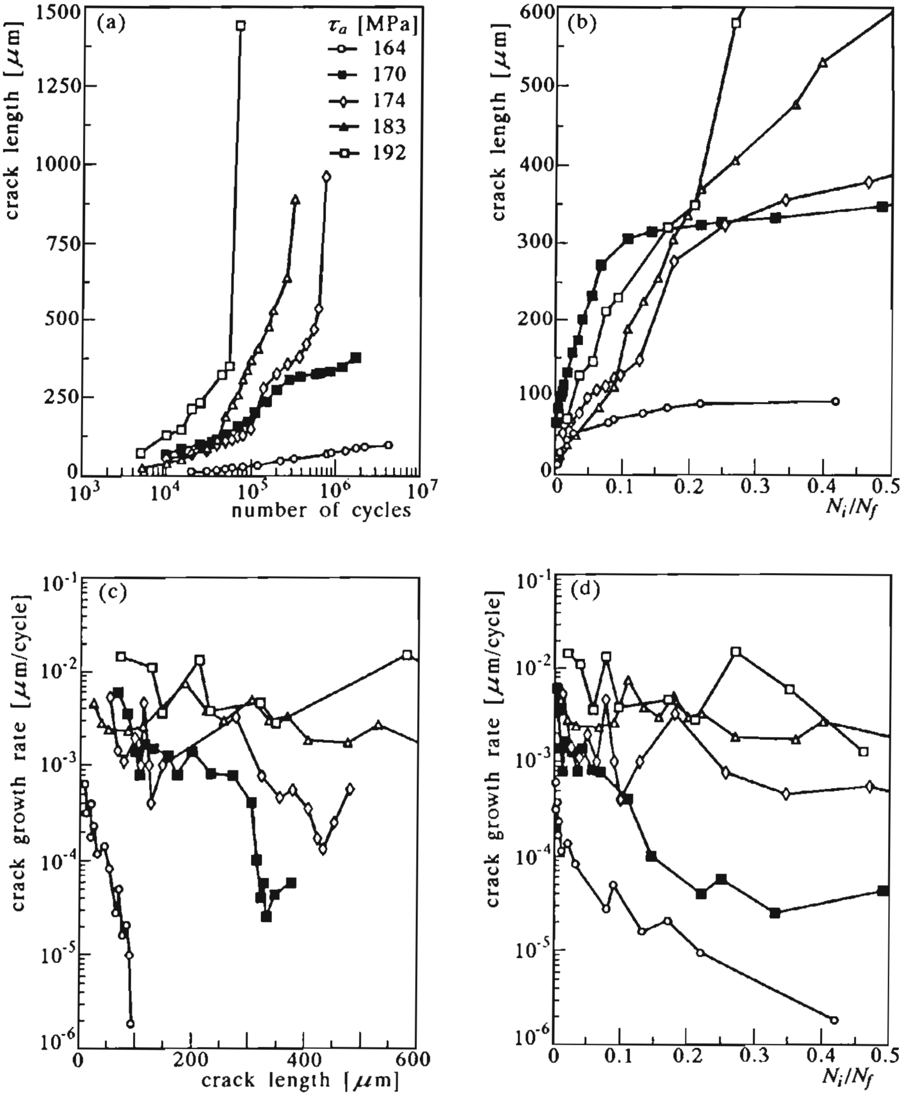

Fig. 7. Plots of crack length versus number of cycles (a) and cycle ratio N_i/N_f (b); crack growth rate versus crack length (c) and cycle ratio (d) drawn for different stress values

crack length and crack growth rate depending on cycles ratio in Fig.7 have been plotted making the assumption of $N_f = 10^8$ cycles. Due to curves in Fig.7b faster crack rise has ocurred at an early stage of propagation in the specimen tested under $\tau_a = 170\,\mathrm{MPa}$ than in another ones. Characteristic behaviour of small cracks has reflected in the course of crack growth rate depending on crack length and cycles ratio in Fig.7c and Fig.7d, respectively. Considerable fall of crack growth rate is observed in specimens investigated under lower stress levels ($\tau_a = 164$, 170 and $174\,\mathrm{MPa}$). When the applied stress level is higher ($\tau_a = 192\,\mathrm{MPa}$) the regime of short crack growth is lost *and average crack growth rate alters in a small range. The courses of crack* growth have attributed to cracks passing by the microstructural barriers with various intensity.

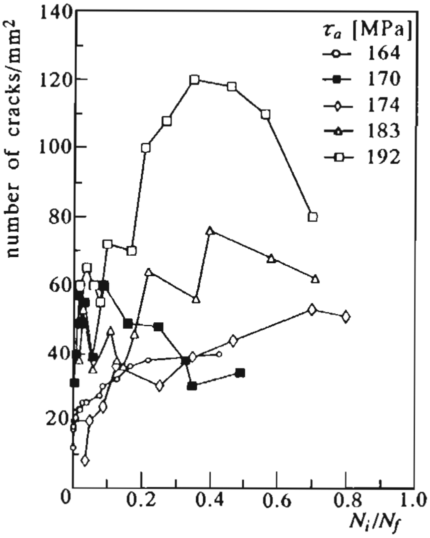

Fig. 8. Short cracks population versus cycle ratio formed in specimens fatigued at different stress values

Surface small cracks analysis has revealed a great number of cracks in an unitary area i.e., $100 \div 120$ cracks/mm^2 (Fig.8). This exceptionally great number of microcracks is one of their characteristic features. On the other hand, great density of microcracks formed at an early stage of fatigue process proves a necessity for improving the prediction of fatigue life of machine parts. The plots in Fig.8 show significant fluctuation of crack population in function of the cycles ratio. Here should be emphasized the share of crack coalescence process in reduction of the crack density. Due to these curves lower crack den-

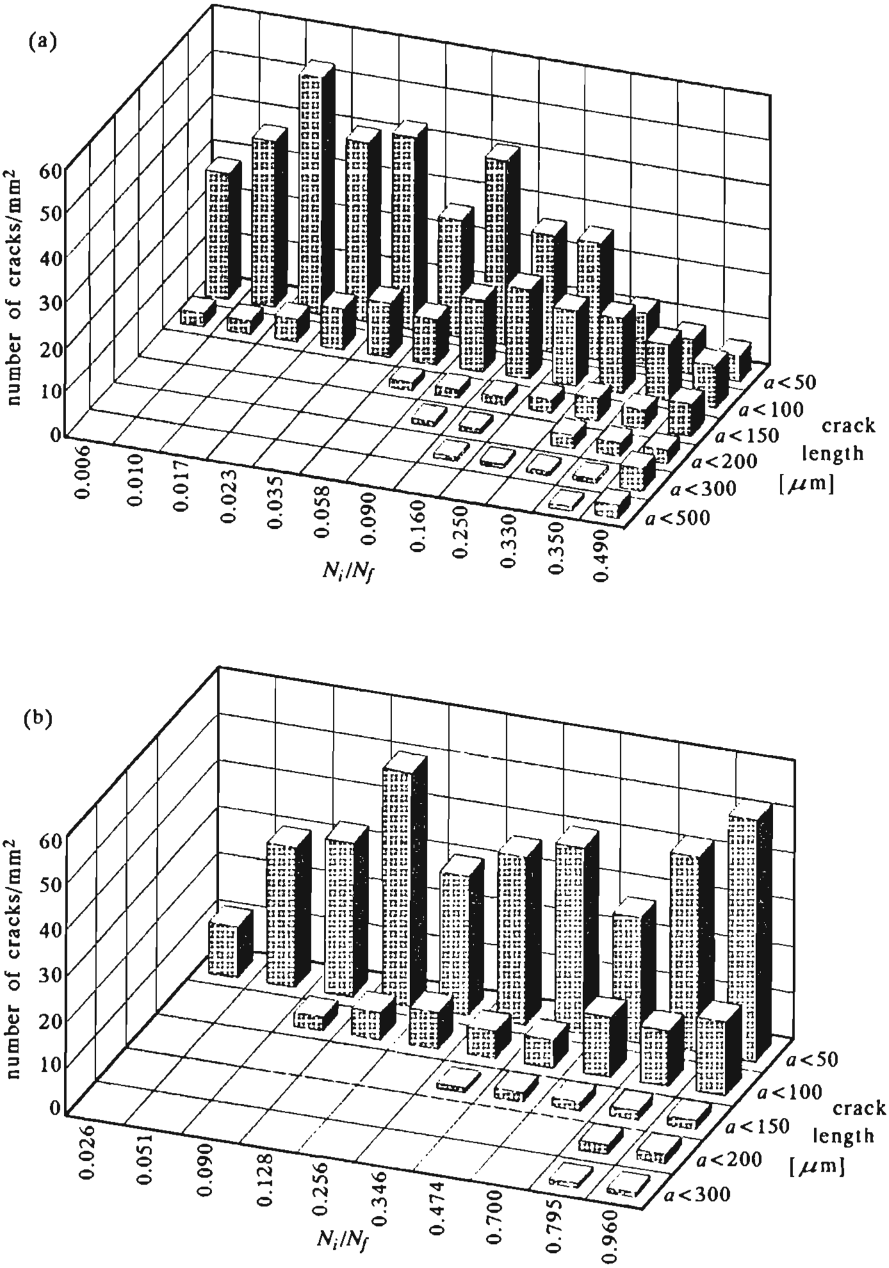

Fig. 9. Distribution of cracks length in specimen tested at torsional stress $\tau_a = 170\,\mathrm{MPa}$ (a) and $\tau_a = 174\,\mathrm{MPa}$ (b) versus cycle ratio

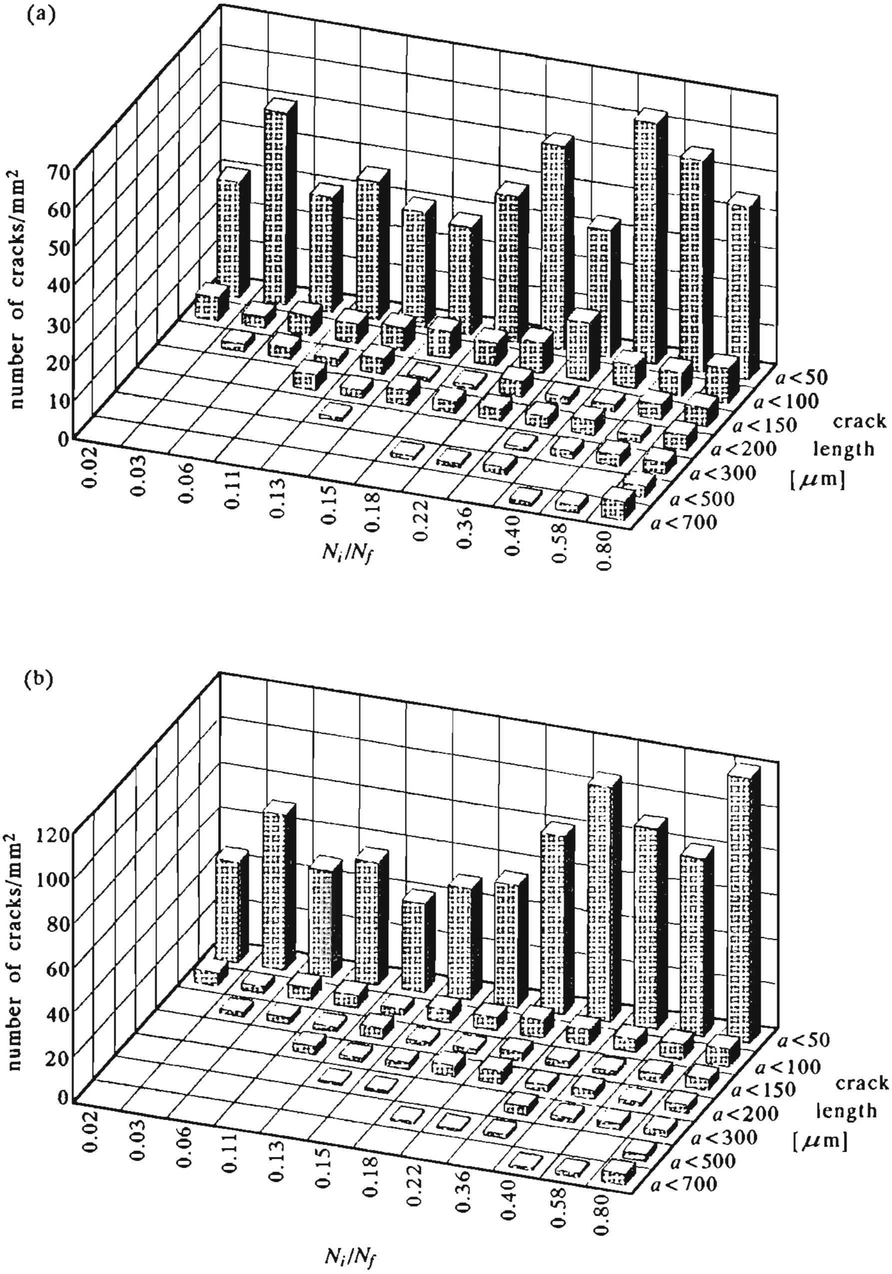

Fig. 10. Distribution of cracks length greater than 20 μm (a) and including microcracks of length less than 20 μm (b) against cycle ratio ($\tau_a = 183\,\mathrm{MPa}$)

sity and any saturation stage of it is observed in the samples tested under lower stress level ($\tau_a = 164, 170, 174\,\mathrm{MPa}$). At higher applied stress ($\tau_a = 183, 192\,\mathrm{MPa}$) the density of cracks has achieved maximum value and then decreased because of crack coalescence. Dynamics of crack propagation and coalescence process can be watched with the help of column diagrams (Fig.9 and Fig.10). The crack lengths have been selected in several groups. Cracks less than $20\,\mu\mathrm{m}$ were disregarded in the diagrams, except in Fig.10b. There may be found a great regularity in the rise of number of cracks $50 \div 100\,\mu\mathrm{m}$ with the increase of cycles ratio in the samples under $\tau_a = 170\,\mathrm{MPa}$ (Fig.9a), $\tau_a = 174\,\mathrm{MPa}$ (Fig.9b). The rise of the shorter crack density is seen in the range of a $0 \div 0.5N_i/N_f$. In further stage of fatigue process the variation of crack density is connected with new created cracks and cracks joining alternatively. In the case of higher applied stress ($\tau_a = 183\,\mathrm{MPa}$, Fig.10) cracks initiation activity begins early since $1 \div 3\%$ of cycles to failure, cracks grow faster and the process of crack coalescence runs speeder. The consequence of those circumstances is a greater variation of crack density observed in Fig.10 and the zigzag courses of plots in Fig.8. In an exemplary diagram in Fig.10b the shortest cracks of length 10 to $20\,\mu\mathrm{m}$ were included as well to reveal the real number of initiated microcracks in the specimen. Neverthless, the value of crack density might introduce errors in the case of indentification the microinclusions inside the ferrite grains with the microcracks. Therefore, to avoid the mistakes only the cracks of length greater than $20\,\mu\mathrm{m}$ were regarded in Fig.8, Fig.9 and Fig.10a.

4. Conclusions

In normalized steel 45 short cracks are initiated and propagate practically in ferrite grains. Direction of crack growth under reversed torsion is determined by the planes of the highest shear stresses, although it is not a rule. A network of the surface microcracks nearly perpendicular to each other is temporarily arrested at the ferrite grains boundaries and most often completely arrested at the pearlite grains boundaries or by the previously initiated cracks. As the result, a significant drop in crack growth rate in the range below a microstructural threshold value is observed. The regime of short crack growth is more visible in specimens fatigued under lower stress applied. At higher stress the cracks have passed faster the microstructural barriers and the drop in crack growth rate has been smaller. Average crack growth rate altered within a smaller range. Other characteristic feature of short cracks is high crack density in an unitary surface area. Depending on the stress applied the density of cracks was to be found 120 cracks/mm^2 at $\tau_a = 192\,\mathrm{MPa}$ and decreased to 40 cracks/mm^2 at $\tau_a = 164\,\mathrm{MPa}$. Dynamics of cracks advance and activity of crack coalescence process have been watched with the help of crack length distribution diagrams. Great density of microcracks formed at an early stage of fatigue process proves a necessity for improving the prediction of fatigue life of machine parts and, on other hand, improving the fatigue resistance of metals. Finally, it should be emphasized that the period of short crack initiation and propagation can be many times as long as the long crack growth period, therefore, it can be decisive for the lifetimes of structural members.

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Krótkie pęknięcia zmęczeniowe w stali 45 wywołane symetrycznym skręcaniem

Streszczenie

Zbadano powstawanie i rozwój krótkich pęknięć zmęczeniowych w próbkach z normalizowanej stali 45 przy symetrycznym skręcaniu. Krótkie pęknięcia powstawały w pasmach poślizgu w ziarnach ferrytu, były częściowo zatrzymywane na granicach tych ziarn oraz blokowane na granicach ziarn perlitu. Podano wykresy przyrostu długości pęknięć, prędkości ich rozwoju, gęstości pęknięć na jednostkowej powierzchni próbek i rozkładów długości pęknięć w zależności od stosunku liczby cykli bieżących do niszczących elementy modelowe.

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