On the Crack Propagation in Low Cycle Fatigue

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Many investigations have been carried out in the field of crack propagation based on the fracture mechanics approach. In low cycle fatigue where the stress or strain amplitude is in the plastic region, the whole material will be under yielding and the idea of plastic enclave will lose its meaning. In the vicinity of the crack the stress intensity is reduced, but that of strain is increased/1/. Since the material just ahead of the crack is subjected to large amplitudes of strain F-R sources will be active in emitting out dislocations. Mott/2/ has suggested that in fatigue the formation of vacancies along the slip line weakens the material and micro-cracks form. Voids have been observed/3/ in front of the advancing fatigue crack. The number of vacancies R that are formed in each dislocation loop is proportional to 'e_p', the plastic strain at the crack tip. This intensified strain is shown/4/ to be $e_p = e\,(1 + C\sqrt{l/p}\;E/E_s)$ where 'e' is the nominal strain, l the crack length, C a constant, 'p' the tip radius and E_s the secant modulus. Let there be n_1 number of dislocation loops along the axis of the crack in the critical length Δl, which is proportional to the maximum displacement at the crack tip, i.e., maximum strain e_p. Vacancies are produced during each cycle in every loop and the growth rate of the void of radius 'a' and width W can be written as $da/dN = C_1\, R\Omega/\, 2\pi W a$. i.e., the rate of void growth is proportional to the plastic strain/5/. When the radius attains a critical value a* in a time ΔN, all the voids join together and form a micro-crack of length Δl which joins the main crack. So the propagation rate can be written as $\Delta l/\Delta N = C_2\, e_p R\Omega/\pi W a^*$. Substituting for R and e_p we get the crack growth rate as $dl/dN = C_3\, (e\sqrt{l})^2$. The quantity $(e\sqrt{l})$ is termed as the strain intensity factor K_e. Integrating we get $\log(l/l_o) = C_4\, e^2\, (N-N_1)$ where N_1 is the nucleation period. When the crack length attains a critical value l_c which is small compared to that at low stress fatigue, fracture occurs. The crack length and the ductility 'e' are connected by the strain intensity relation and so the remaining ductility e_R due to fatigue crack can be shown/6/ to be $\log(e_R/e_f) = -C_5\, e^2\, (N-N_1)$ where $N_1 << N$.

Experimental: The material used were 18-8 steel, heated to 1050°C and oil quenched and commercially pure aluminium annealed at 350°C for one hour. The UTS for 18-8 was 60kgf/sqmm and that of Al was 14.7kgf/sqmm. The fracture strains e_f were 65% and 22% respectively. Crack propagation tests were carried out in a hydraulic pulsator with a frequency of 40/min. A small starter crack to a depth of 0.5 mm was introduced in all specimens to localize the nucleation and propagation of the fatigue crack. The propagation was observed through a travelling microscope with an accuracy of 0.01mm. The plastic strain at half life was measured over a gage length of 50 mm. The fatigue ductility tests were carried out in a PUPN rotary bending machine at a frequency of 2700/min. The stress levels were 21.4 kgf/sqmm for 18-8 and 9.1, 8.2 and 7.0 kgf/sqmm for aluminium.

Results and Discussion: Fig.(1) shows the variation of the plastic strain with notch depth. When the maximum strain e_p at the notch tip attains a critical value e_f the fracture starts. The full line gives the theoretical relation with 'C' around 2. In fatigue the tip radius 'p' will be very small and so the strain intensity will be $e\sqrt{l}$. In low cycle fatigue this strain intensity appears to control the crack growth rate which is found to be proportional to $(e\sqrt{l})^2$. Fig.(2) gives the relation between $e\sqrt{l}$ and dl/dN on a log-log plot for two mean crack lengths. The slope of the line is found to be 2. The relation also implies that in high stress/strain fatigue dl/dN is proportional to 'l', i.e., $\log(l/l_o) = C_6\, N$. Fig.(3) shows the fatigue crack growth with the number of cycles on a semi log plot. Fig.(4) gives the relation between the remaining ductility e_R and the number of cycles to which the specimen was subjected before removed for tensile test. The experimental results appear to support the theoretical relation namely, $\log(e_R/e_f) = -C_7\, e^2\, N$.

References:

/1/ McClintock, F.A. Trans. ASME (E), 30 (1963) 631.

/2/ Mott, N.F. Dislocations & Mech. Prop. of Crystals. John Wiley & Sons. London. (1956) 458.

/3/ Ogura, T. & Karashima, S. Trans. JIM, 10 (1969) 292.

/4/ Radhakrishnan, V.M. Scripta Met. 5 (1971) 379.

/5/ Gittins, A. Discussion. Met. Sci. J. 4 (1970) 238.

/6/ Radhakrishnan, V.M. Scripta Met. 5 (1971) 855.

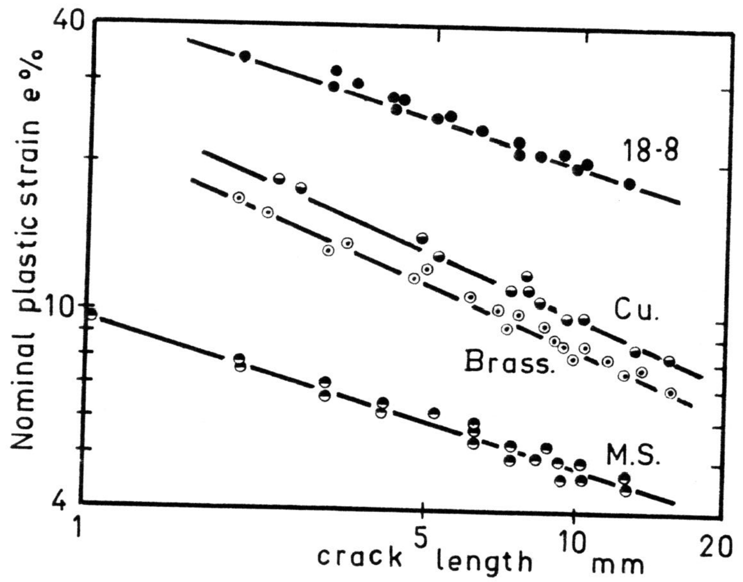
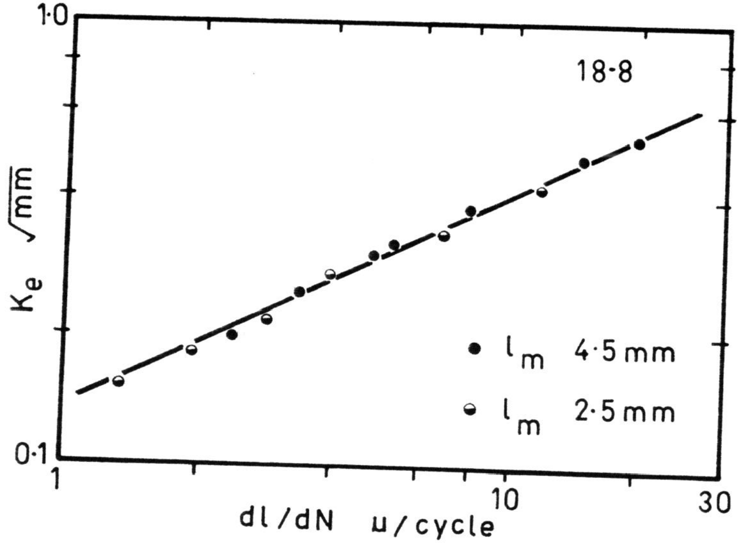
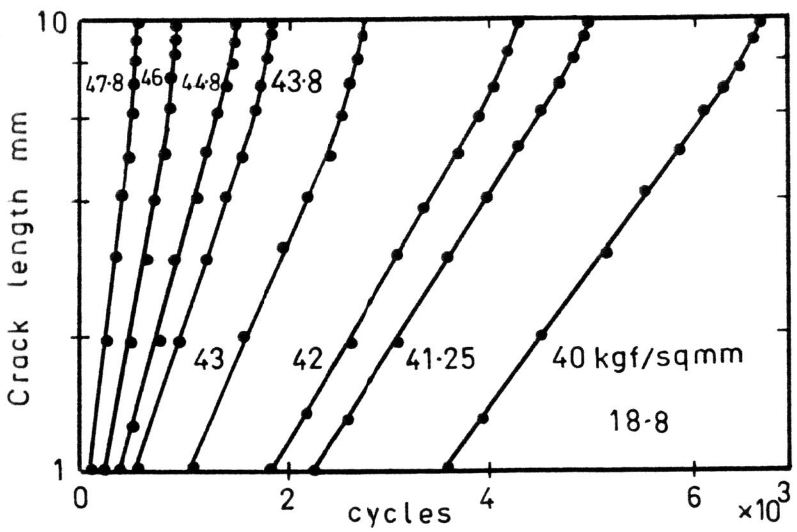


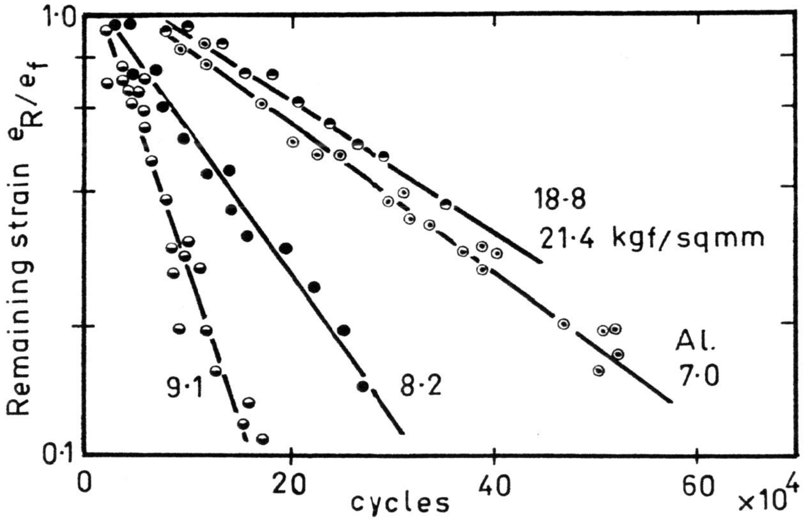
Fig.(1). Effect of notch depth on plastic strain.



Fig(2). Crack growth rate with strain intensity factor.



Fig(3). Crack growth with fatigue cycling.



Fig(4). Exhaustion of ductility with fatigue cycling.