MICROMECHANISMS OF FATIGUE FRACTURE

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ABSTRACT

Fatigue fracture micromechanisms of different alloys are considered with respect to peculiarities of plastic deformation and macroscopic curve of fatigue crack growth rate on the base of results obtained. The problems of striation formation mechanism, the reasons for plastic zone value dependence of striation formation concerning the microstructure parameter (diameter of grain), the reasons for the lack of coincidence between the macro and microrates of crack growth and the possibility of critical point determination on the crack growth diagram using the analysis of fracture micromechanism are discussed.

INTRODUCTION

Application of the linear fracture mechanics to fatigue led to a substantial progress in the studies of its kinetics. But the micromechanisms of plastic deformation and fracture on the stage of fatigue crack growth are yet investigated much less. This paper deals with the fatigue fracture micromechanisms of some experimental and commercial alloys concerning peculiarities of the plastic deformation and macroscopic curve of fatigue crack growth rate, as well as the effect of vacuum and low temperature on them.

MATERIALS AND EXPERIMENTAL

The alloys Cu-7.5%Al, Fe-3.7%Si, Al-6%Mg, Mg-4%Al-0.8%Zn (MA2-I), Mg-5%Al-8%Li-5%Cd (MA2I) in annealed state, Mg-3%Nd-0.45%Zr (MAI2) in annealed and heat hardened states and Mg-8%Y-0.5%Cd (IMB6) in hot worked state were investigated. The experiments were carried out on flat samples (1 mm thickness, soft side notch) at the cyclic cantilevered symmetric bent and on unnotched cylindrical samples (5 and 6mm diameter) in cyclic tension-compression. The investigations were accomplished in atmosphere and in vacuum of 10^{-7}torr at 293 K and in vacuum at 153 K as well. The fatigue fracture zone microstructures have been studied by the aimed TEM studies of two-step plastic-carbon replicas at the fixed fatigue crack length. The local microrate was determined by the spacing between fatigue striations. The microrate of crack growth was measured on the sample surface by means of optical microscope with 500-fold magnification. The depth of plastic zone around fatigue crack was measured by X-ray technique by successful filming and removing layers from fracture surface by electropolishing. Depth of macroscopic plastic zone was determined according to the surface darkening around fatigue crack during its propagation.

RESULTS AND DISCUSSION

Typical microstructure of crack fatigue fracture are striations, which denote the successive positions of its front. Mechanisms of their formation were often discussed [1-4], and Laird's hypothesis seems to be the most realistic and universal [2,4,5]. However, its deficiency is that it cannot explain the lack of striations at cyclic loading in vacuum [5]. This phenomenon was revealed in aluminium and titanium alloys [1,3,6], and it was usually ascribed to the change of crack growth mechanism under medium influence. However, investigations of the alloys with inhibited cross slip Fe-3.7%Si, Cu-7.5%Al) showed that in samples deformed in vacuum striations formed are as pronounced and regular as in the air (Fig. 1) [7-9].

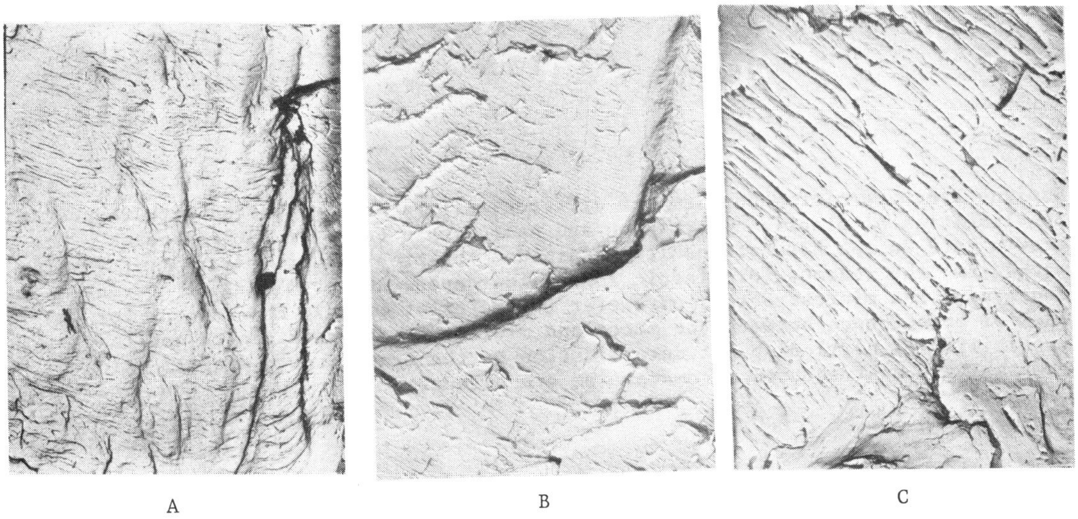


Fig. 1 Striations at fractures of fatigue specimens of Fe-3.7%Si cycled in vacuum (a) and in air (b,c) at deformation amplitudes 0.0026 (a,b) and 0.0037 (c). X7000.

They arrange in the whole fatigue zone, whose length depends on deformation amplitude and the environment. As the value of deformation amplitude increases the striated zone decreases in vacuum faster than in air. And it disappears in vacuum at the lower deformation amplitude than in air. (Fig. 2)

Since a striation is formed in the plastic deformation zone the influence of medium on this region must be considered. It has been shown [10-12] that in vacuum the size of macro- and microscopic plastic zone is greater than in the air at the same ΔK value (Fig. 3). This is particularly typical for plastic materials. In alloys, where the plastic deformation is inhibited, the plastic zone in vacuum is nearly similar to that formed in the air [8]. Since striations form only at the restricted crack length and, thus, in some definite plastic zone size, one may assume that the lack of striations in aluminium alloys in vacuum is due to the essential increase of plastic zone in this environment.

The following experimental data evidence is the favour of this assumption. Striations were clear and regular in the fatigue zone of aluminium - 6%Mg [13] and

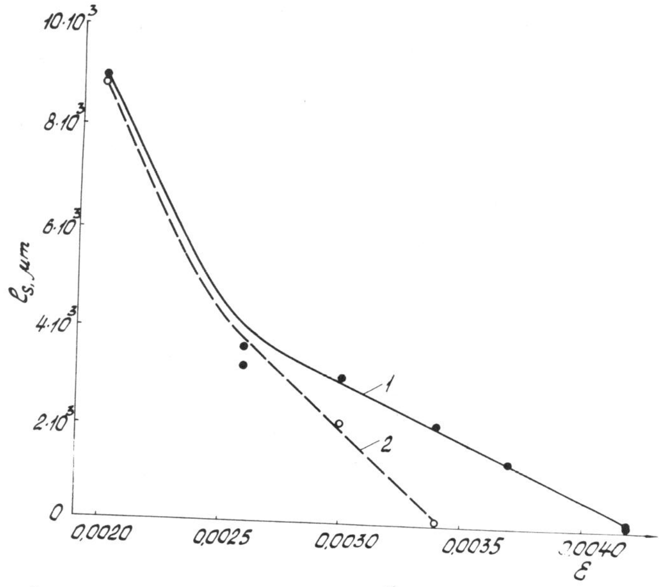


Fig. 2. Depth of Striation zone ℓ_s vs deformation amplitude (1) in air and (2) in vacuum for Fe-3.7%Si alloy.

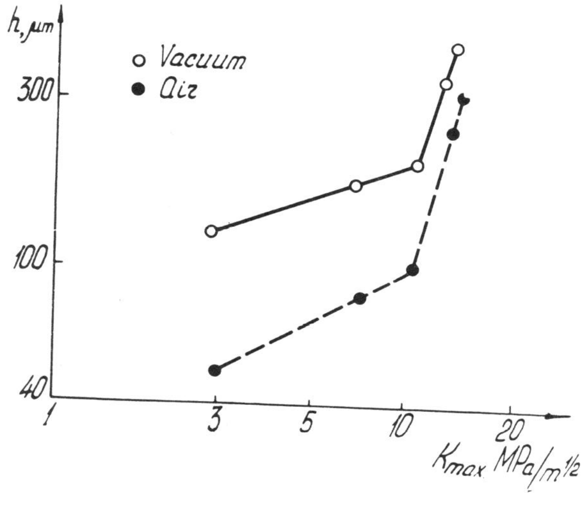


Fig. 3. Plastic zone depth vs stress intensity factor K_{max} for magnesium alloy MA12 (T6)

magnesium - yttrium [14] alloy samples fractured in air and striations were rare and badly pronounced in this region in vacuum (Fig. 4a and b). The reduction of temperature of cyclic deformation from 293 to 153 K, resulting in decrease of plastic zone size, led to the formation of as regular and pronounced striations in the vacuum as in the air (Fig. 4c).

In [15,16] is shown that formation of the striations occurs at the rates corres-

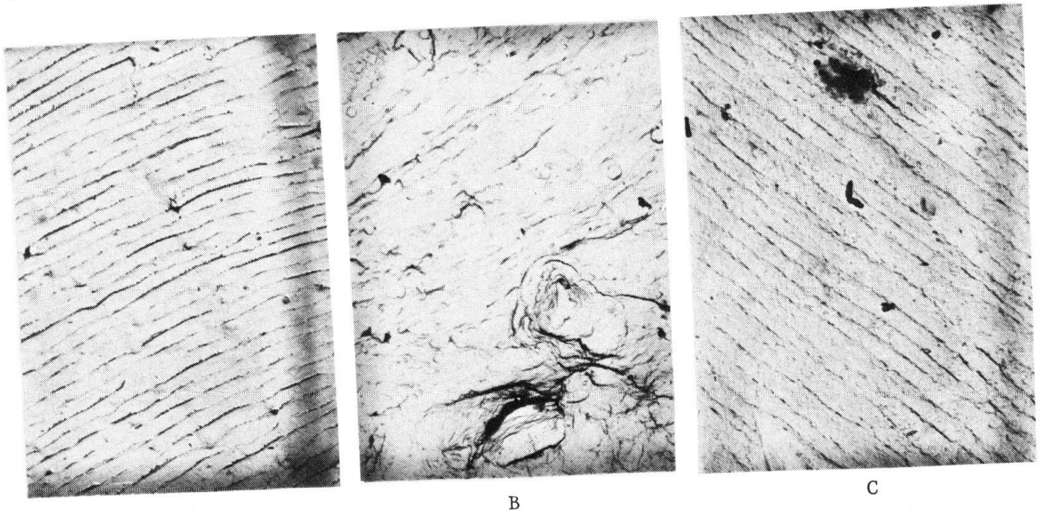
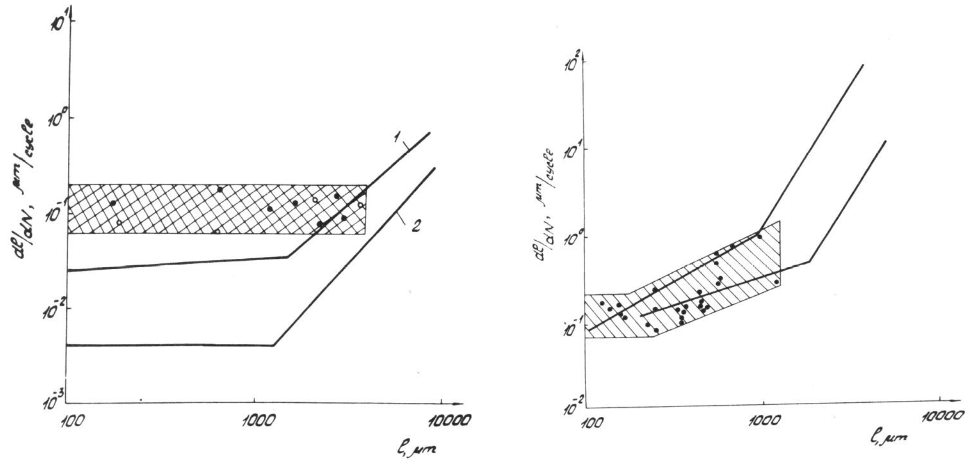


Fig. 4. Electron fractographs of specimens of Al-6%Mg cycled (a) in air at 293 K, (b) in vacuum at 293 K and (c) in vacuum at 153 K. X7000.

ponding to the region of Paris diagram, where the plastic zone value is h = 1 - 4d, where d is the grain diameter. Probably, to produce a striation by plastic relaxation mechanism an elastic constrain of certain degree is needed from neighbouring grains. If it reduces because of growth of plastic zone size, this process becomes irregular or does not take place at all. These ideas about the mechanism of striation formation explain its absence in some plastic alloys in vacuum, corroborate the identity of crack growth mechanisms in vacuum and in atmosphere and the universality of Laird's hypothesis.

Investigations of some steels and alloys have shown that striations are formed by each loading cycle and microrate, determined by the striations spacings, increases during the crack growth and coincides with the macrorate measured by means of other techniques [2,3]. This situation is but not common. When studying the crack growth in flat samples of silicon iron it was found [7,8] that macrorate was constant independent of crack length and deformation amplitude value in high cyclic loading legion and the same in the air and in vacuum. Its range is from 5.10^{-2} to 2.10^{-4}mm/cycle (Fig.5a). The value of macrorate, measured optically on the sample surface, is lower than the microrate value. Thus, when loading with deformation amplitude ε = 0.0020 in the stage of slow crack growth the microrate exceeeds the macrorate by a factor of 17 in the air and almost by a factor of 400 in vacuum. With the increase of deformation amplitude this difference in rates decreases, still in vacuum it is much more greater than in the air, because of the lower microrate in vacuum. And only at the deformation amplitude of 0.0037, corresponding to the transition to low cyclic loading region, striation spacings begin to increase and macrorate coincides with the microrate (in the air) (Fig. 5b). Striations do not appear at the same deformation in vacuum.

The above regularities (the lack of coincidence between the macro and microrates the constancy of macrorate value with the growth of crack length to some definite size and the equality of microrates in the air and in the vacuum) are typical also for the Cu-7.5%Al [9] alloy samples. It has been stated that the coincidence of macro- and microrate takes place when the plastic zone reaches a value equal to 2 or 3 grain diameters. This also results in a sharp increasing of crack growth rate evident from the curve inflection dl/dN = f(1). This allowed to suppose, that



A B

Fig. 5. Fatigue crack growth in Fe-3.7%Si vs crack length in air and in vacuum for deformation amplitude (a) -0.0026, (b) -0.0037.

1 - macroscopic rate in air, 2 - macroscopic rate in vacuum, ● ▧ - microscopic rate in air, ○ ▨ - microscopic rate in vacuum.

the lack of correlation between macro and microrates in the high-cyclic region is associated with the fact, that at low ΔK the plastic zone is small and striations are formed not by each loading cycle but by the last from a series of cycles. In the course of such stops plastic deformation accumulates at the crack end. With the increase of ΔK (that is, of crack length or stress) number of cycles in a series decreases because the accumulation of plastic deformation needed for striation formation increases. It seems to be peculiar to small striations on the surface of flat samples. Coincidence of macro- and microrates is typical only for the motion of microscopic cracks, when plastic zone is equal to 1 - 4 grain diameters.

In vacuum the accumulation of plastic deformation, needed for striation formation at the same ΔK value, occurs during a higher number of cycles. This is explained by the fact that dislocation escape to the crack surface in vacuum is facilitated by the absence of adsorbed or oxidized layer and as a result of this the dislocation concentration in the subsurface layer is lower than in the air. It should be mentioned that the striation formation in the fatigue region is not the only micromechanism of crack growth at cyclic loading. Thus, for example, investigation of a number of magnesium alloys has shown that at the same values of ΔK (K_{max}) the micromechanism of fatigue fracture depends on the initial structural state [14,17]. In annealed alloys with large intermetallic particles fracture occurs with the formation of brittle intra- and intergrain structures typical for quasistatic fracture. In two-phase magnesium-lithium alloy the crack growth occurs according to the ductile quasistatic mechanism. And the formation of striations was observed only on heat-hardened alloys, in which the dynamic work hardening takes place. Dimensions (and probably microstructures) of plastic zone depend on the alloy structural state [10]. In the first group of alloys its size is lower than the minimum value, needed for the striation formation, and fracture mechanism is a brittle one. When the maximum value is exceeded the fracture mechanism is a ductile one and striations form only at a definite average value of plastic zone.

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