TECH SPOTLIGHT

FATIGUE CRACK PROPAGATION

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Basically, fatigue crack propagation can be divided into three stages: stage I (short cracks), stage II (long cracks) and stage III (final fracture).

- **Stage I:** Once initiated, a fatigue crack propagates along high shear stress planes (45 degrees), as schematically represented in Fig. 1. This is known as stage I or the short crack growth propagation stage. The crack propagates until it is decelerated by a microstructural barrier such as a grain boundary, inclusions, or pearlitic zones, which cannot accommodate the initial crack growth direction. Therefore, grain refinement is capable of increasing fatigue strength of the material by the insertion of a large quantity of microstructural barriers, i.e. grain boundaries, which have to be overcome in the stage I of propagation. Surface mechanical treatments such as shot peening and surface rolling, contribute to the increase in the number of microstructural barriers per unit of length due to the flattening of the grains.

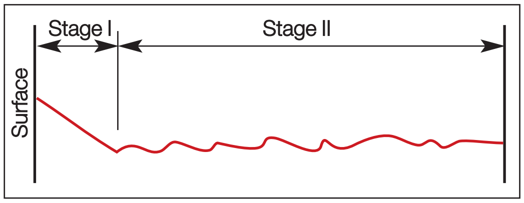

Fig. 1— Stages I and II of fatigue crack propagation.

- **Stage II:** When the stress intensity factor K increases as a consequence of crack growth or higher applied loads, slips start to develop in different planes close to the crack tip, initiating stage II. While stage I is orientated 45 degrees in relation to the applied load, propagation in stage II is perpendicular to the load direction, as depicted in Fig. 1.

An important characteristic of stage II is the presence of surface ripples known as "striations," which are visible with the aid of a scanning electron microscope. Not all engineering materials exhibit striations. They are clearly seen in pure metals and many ductile alloys such as aluminum. In steels, they are frequently observed in cold-worked alloys. Figure 2 shows examples of fatigue striations in an interstitial-free steel and in aluminum alloys. The most accepted mechanism for the formation of striations on the fatigue fracture surface of ductile metals, is the successive blunting and re-sharpening of the crack tip, as represented in Fig. 3.

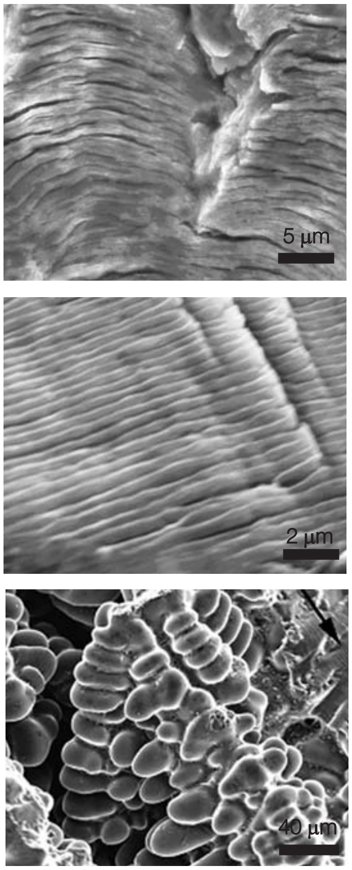

Fig. 2 — Fatigue striations in (a) interstitial free steel and (b) aluminum alloy AA2024-T42. Figure (c) shows the fatigue fracture surface of a cast aluminum alloy, where a fatigue crack was nucleated from a casting defect, presenting solidification dendrites on the surface; fatigue striations are indicated by the arrow, on the top right side.

- **Stage III:** Finally, stage III is related to unstable crack growth as K_{max} approaches K_{IC}. At this stage, crack growth is controlled by static modes of failure and is very sensitive to the microstructure, load ratio, and stress state (plane stress or plane strain loading).

Macroscopically, the fatigue fracture surface can be divided into two distinct regions, as shown by Fig. 4.The first region corresponds to the stable fatigue crack growth and presents a smooth aspect due to the friction between the crack wake faces. Sometimes, concentric marks known as "beach marks" can be seen on the fatigue fracture surface, as a result of successive arrests or decrease in the rate of fatigue crack growth due to a temporary load drop, or due to an overload that introduces a compressive residual stress field ahead of the crack tip.

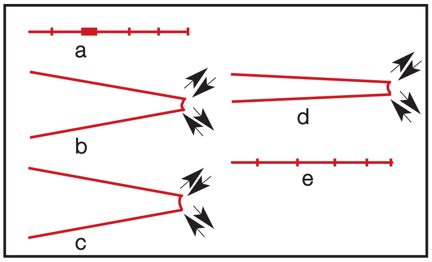

Fig. 3 — Laird´s proposed mechanisms of striation formation in the stage II of propagation: (a) no load; (b) tensile load; (c) maximum tensile load; (d) load reversion and (e) compressive load.

- **Final fracture:** The other region corresponds to the final fracture and presents a fibrous and irregular aspect. In this region, the fracture can be either brittle or ductile, depending on the mechanical

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* Fellow of ASM International and member of the ASM Heat Treating Society

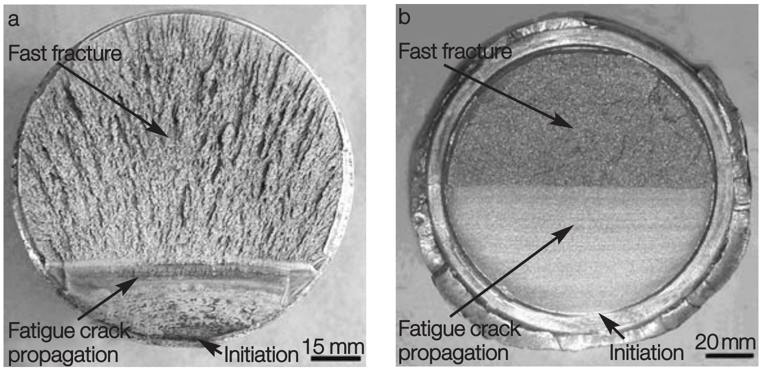

Fig. 4 — *Fatigue fracture surface: (a) high applied load; (b) low applied load.*

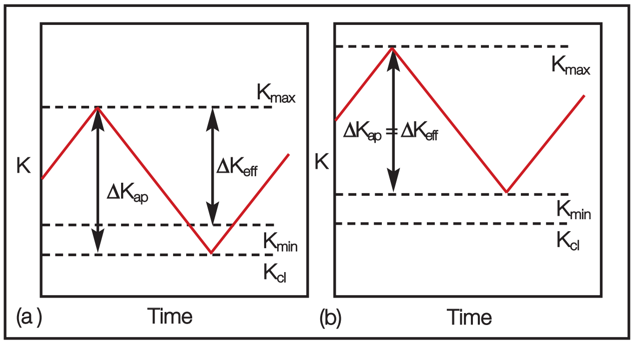

Fig. 8 — *Load ratio effect on ΔK_{eff}, in a fatigue cycle: (a) $K_{min} < K_{cl}$ (b) $K_{min} > K_{cl}$*

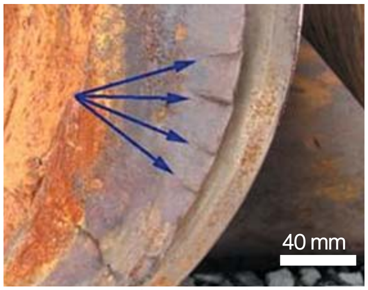

Fig. 5 — *Ratcheting marks, indicated by the arrows, in a SAE 1045 shaft fractured by fatigue.*

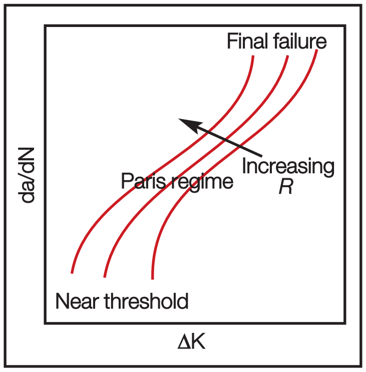

Fig. 6 — *Schematic representation of the R ratio effect on fatigue crack growth curves. The near threshold, Paris regime, and final failure regions are also indicated on the curves.*

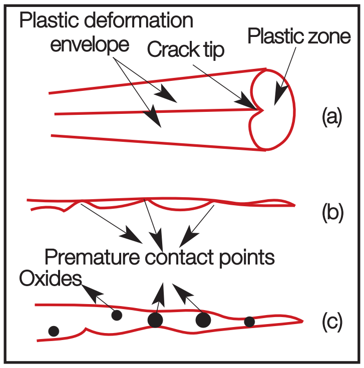

Fig. 7 — *Crack closure mechanisms induced by: (a) plasticity, (b) roughness (c) oxide.*

properties of the material, dimensions of the part, and loading conditions.

The exact fraction of area of each region depends on the applied load level. High applied loads result in a small stable crack propagation area, as depicted in Fig. 4. On the other hand, if lower loads are applied, the crack will have to grow longer before the applied stress intensity factor *K*, reaches the fracture toughness value of the material, resulting in a smaller area of fast fracture, Fig. 4b.

- **Ratcheting marks:** Ratcheting marks are another macroscopic feature that can be observed in fatigue fracture surfaces. These marks originate when multiple cracks, nucleated at different points, join together, creating steps on the fracture surface. Therefore, counting the number of ratchet marks is a good indication of the number of nucleation sites. Figure 5 presents in detail some ratchet marks found on the fracture surface of a large SAE 1045 rotating shaft fractured by fatigue.

Propagation rates

Similarly to the initiation phase, many factors can affect long fatigue crack propagation rates. Among them, special attention should be given to effects of load ratio and the presence of residual stresses.

Increasing the load ratio has a tendency to increase the long crack growth rates in all regions of the curve plotting fatigue crack growth rate versus applied stress intensity factor range, or simply the curve of *da/dN* versus applied ΔK. Generally the effect of increasing load ratio is less significant in the Paris regime than in near-threshold and near-failure regions, Fig. 6.

Near the threshold stress intensity factor, ΔK_{th}, the effects of *R* ratio are mainly attributed to crack-closure effects, in which crack faces contact each other at an applied K_{cl} that is higher than the minimum applied stress intensity factor, K_{min}.

Several different mechanisms may contribute to premature crack closure. One consists of plasticity-induced closure, represented in Fig. 7a. As the crack grows, the material that has been previously permanently deformed within the plastic zone now forms an envelope of plastic zones in the wake of the crack front. This leads to displacements normal to the crack surfaces as the restraint is relieved. This is no problem while the crack is open; however as the load decreases, the crack surfaces touch before the minimum load is reached, shielding the crack. This type of premature contact can also occur due to crack wake roughness and irregularities, Fig. 7b, or by the presence of corrosion sub-products such as oxides, Fig. 7c.

As observed in Fig. 8, the effect of closure produces a reduction in the effective ΔK range because of the increase in the effective K_{min}, reducing the driving force for fatigue crack growth. The effect is more significant near the threshold region because the crack tip opening displacements are smaller and crack faces are closer to each other. Additionally, for the same applied ΔK, higher *R* ratios increase the applied values of K_{max} and K_{min}, increasing ΔK_{eff}.

For most materials, the Paris regime is considered "closure-free and K_{max}-independent" and the crack growth rates are generally very similar for tests conducted under different *R* ratios. Near the final failure, the effects of *R* ratio are related to the higher monotonic fracture component as K_{max} approaches K_{IC}.

Therefore, for the same applied ΔK, K_{max} values are higher for tests conducted under higher applied *R* ratios, and consequently, *da/dN* values are higher.

The effects of residual stress on fatigue crack growth are related to alterations in the *R* ratio and in the applied ΔK. In other terms, the residual stresses affect the two parameters that control the crack driving force, i.e. K_{max} and ΔK_{eff}. When a crack is introduced in a plate subjected to a residual stress field, a residual stress intensity factor K_r, arises that can either decrease or increase the crack driving force parameters.

The superposition principle can also be applied

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in terms of the stress intensity factor, provided that the material remains linearly elastic. In this sense, K_r can be added to K_{max} and K_{min}:

$$K'_{max} = K_{max} + K_r$$

$$K'_{min} = K_{min} + K_r$$

As a result, R' and $\Delta K'$ are defined as follows:

1. If $K'_{min} > 0$ then:

$$R' = \frac{K'_{min}}{K'_{max}} = \frac{K_{min} + K_r}{K_{max} + K_r}$$

$$\Delta K' = K'_{max} - K'_{min} = (K_{max} + K_r) - (K_{min} + K_r) = K_{max} - K_{min} = \Delta K$$

2. If $K'_{min} \leq 0$, then:

$$R' = 0$$

$$\Delta K' = K'_{max} = K_{max} + K_r$$

It is important to note that these equations assume that the part of the fatigue cycle during which the crack is closed at its tip (i.e. $K'<0$) makes no contribution to crack growth. ◆

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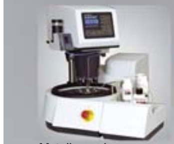
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