Fatigue Crack Growth in Metals under Pure Mode III: Reality or Fiction?

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ABSTRACT. *The possibility of a pure Mode III crack growth is analyzed on the background of theoretical and experimental results achieved in the last 20 years. Unlike for Modes I and II, there is no plausible micromechanistic model explaining a pure Mode III crack growth in ductile metals. In order to realize "plain" Mode III fracture surface, we propose a propagation of a series of pure Mode II cracks along the crack front. Fractographic observations on crack initiation and propagation in a low alloy steel under cyclic torsion support such a model. The authors do not see any clear indication of a pure Mode III micromechanism in ductile metals till now.*

INTRODUCTION

It is well known that, on the macroscopic scale, stage II fatigue cracks generally tend to grow in Mode I [1]. As a rule, cracks initially growing in macroscopically pure shear Modes II and III branch to planes dominated either by the maximum tensile stress component at the crack front or by the bulk stress fields. In the presence of pure Mode III displacements at a crack front, Mode I branch cracks often develop to produce a so-called twist crack. Also a shear dominated crack growth in a macroscopic Mode III usually proceeds, on a microscopic scale, as a mixture of Modes I+III or II+III, since a great majority of crack front elements are not strictly parallel to the applied anti-plane shear stress direction.

Many authors studied a macroscopically pure Mode III crack growth in metallic materials under cyclic torsion by using cylindrical specimens with circumferential or elliptical notches and precracks (e.g., [2-8]). A relatively short initial period of crack growth in the shear Modes II, II+III and III was observed before the onset of a Mode I dominated propagation due to the branching of Mode II crack front segments forming a factory roof fracture morphology. In the low cycle fatigue region, a macroscopically flat, shear dominated fracture appeared in most cases. The presence of a pure Mode III growth was deduced from the macroscopical appearance of the crack growth direction and from the existence of fibrous patterns parallel to the assumed crack front. However, while the principal micromechanisms of fatigue crack growth under Modes I and II are well known and sufficiently clear, there is a lack of any plausible interpretation in case of a pure Mode III crack propagation.

The aim of the paper is to present a possible micromechanical interpretation of a Mode III crack growth based either on an alternating Mode II model or on a Mode II mechanism acting between cracked particles near the crack front. It will be shown that the fractographic features can be misleading since Mode II mechanisms can also produce crack front sequences parallel to the assumed “Mode III” front. Some experimental observations of cracks developing under cyclic torsion are discussed in terms of those non-Mode III mechanisms.

MODE II MODELS SIMULATING MODE III CRACK GROWTH

Fatigue crack propagation in ductile metals is usually explained by the cyclic plastic deformation of the crack tip [9-11]. The basic difficulty with a pure Mode III mechanism in homogeneous materials can be simply understood following the crack growth schemes drawn in Fig. 1. During one loading cycle, new surfaces are created ahead of both Mode I and Mode II fatigue crack fronts by non zero components of shear displacements parallel to the crack growth direction. Environmental degradation of newly created surface and irreversibility of dislocation movement are commonly accepted reasons for an incomplete recovery of atomic bounds at the crack tip during reversal loading. On the other hand, no shear displacements creating such new surfaces are produced by a pure Mode III loading. In what follows, we will discuss explanations for deformation based Mode III crack propagation, for:

- straight crack front
- tortuous crack front and
- micro crack initiation along the crack front by fracturing of secondary phase particles or decohesion of particle matrix interfaces

Straight Crack Front

As mentioned above no shear displacements creating new surfaces are produced by a pure Mode III loading. The out-of-plane shear stresses can create new crack surfaces only on both sides of an interior crack inside the bulk, or in front of alternating surface steps along the side surfaces of a through-the-thickness crack (Fig. 1). Consequently, Mode III cracks can grow in homogeneous materials only in the direction parallel to its crack front inside the bulk (local Mode II), but not in the perpendicular direction. It should be emphasized, however, that what looks macroscopically like a Mode III crack front propagation does not need to be produced necessarily by pure Mode III displacements. Pure Mode II cracking micromechanisms can be exclusively responsible for such crack front advance. In homogeneous materials it demands only one assumption – a microscopically tortuous crack front.

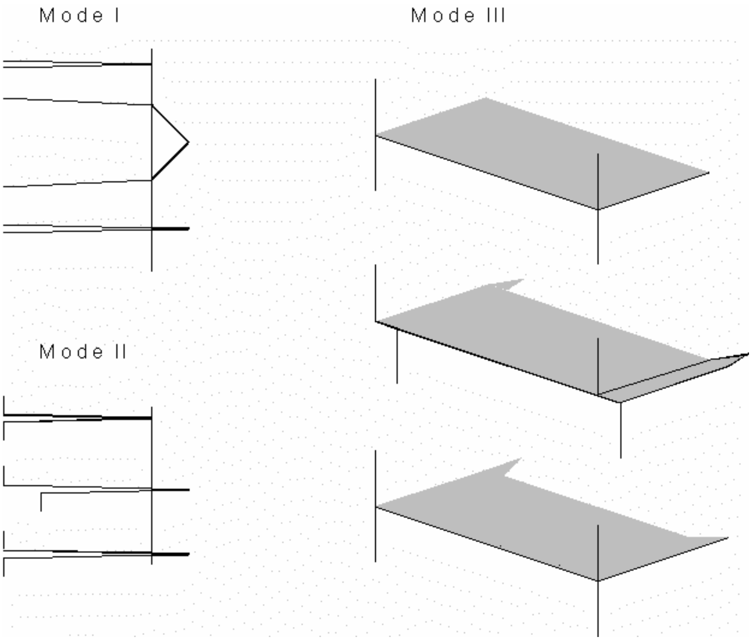

Figure 1. Schemes of fatigue crack growth in Modes I, II and III based on crack tip deformation.

Microscopically Tortuous Straight Crack Front

Let us consider a simple model of a macroscopically straight, but microscopically tortuous, crack front under a pure macroscopic Mode III loading – see Fig. 2. The triangular microlegs are loaded in a mixed-Mode II+III, but the out-of-plane shear stress vector can be resolved into two pure Mode II (in-plane) components, perpendicular to the

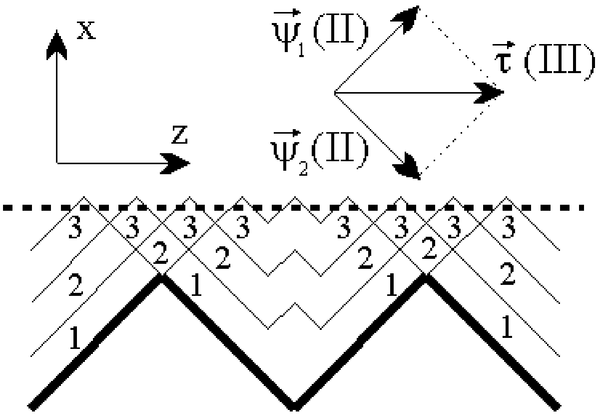

Figure 2. Scheme of the alternating pure Mode II mechanism leading to a gradual advance of a microscopically tortuous straight crack front in a macroscopic Mode III. The thin lines indicate positions of the crack front after specific fatigue cycles.

triangle legs. This enables an alternating step-by-step growth of the crack front segments under a pure Mode II mechanism. As a result of the overlapping crack tip fields [12], a higher crack growth rate can be assumed near the trailing corners of the crack; a lower crack growth rate can be assumed at the foremost tips of the crack. This leads to a gradual smoothing of the crack front that remains to be parallel to the macroscopic crack front direction and the observed fractographic “Mode III” patterns are misleading. The macroscopic crack front propagates in the *x* direction and the crack front becomes gradually smoothed. The first effect can elucidate a Mode III-like fatigue crack growth from a circumferential Mode I precrack (stabilizing a shear Mode controlled growth) under torsion observed, e.g. by Tanaka et al. [6] and Murakami et al. [8]. The latter effect - the smoothing of the crack front - may decelerate the macroscopic Mode III crack growth or even cause its arrest. Such a behavior, reported already by Tschegg [2,4,7], has been attributed up to now only to the surface friction.

Growth Initiated from Semicircular Surface Precrack

Propagation of a crack starting from a semicircular surface precrack under pure macroscopic Mode III is shown in Fig. 3. The above alternating Mode II, step by step, advance of the crack front segments is used also in this scheme. Although the depth-to-width proportion of the crack front must depend on the Mode II crack growth rate curve of a particular material, the resulting shape of the growing crack becomes always qualitatively very similar to that experimentally observed by Murakami [13]. Note that the straight segments of the precrack front used in the model might be arbitrarily shortened (and multiplied) in order to approach a semicircular shape. Moreover, it

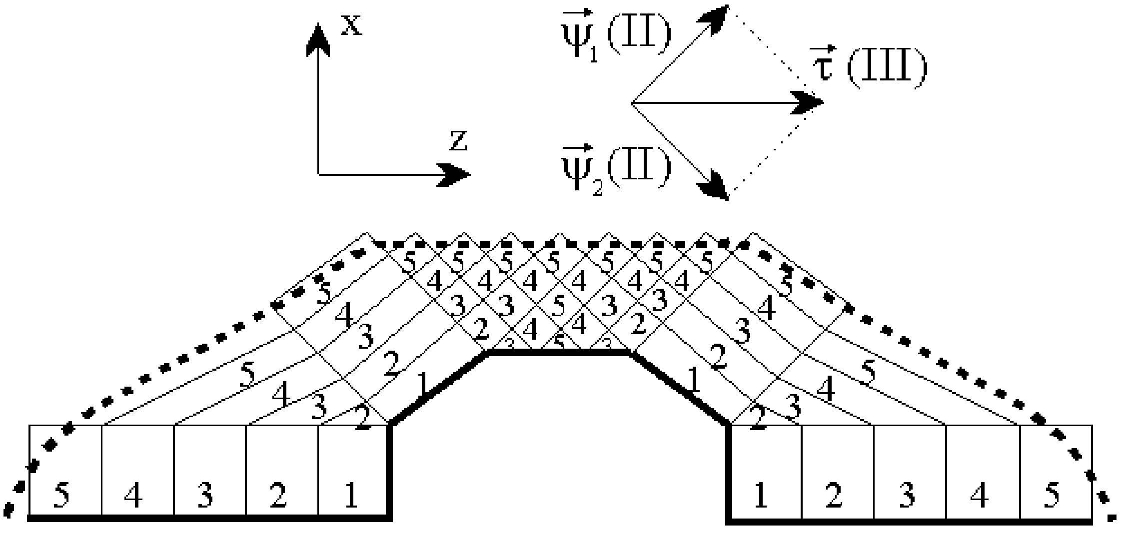

Figure 3. Scheme of Mode II growth mechanisms operating in front of a semi-circular surface crack. In the middle section it seems that the crack propagates as a pure Mode III crack.

should be emphasized that, in spite of a large horizontal (microscopically smooth) crack front segment, the shape of the crack front after a certain number of cycles gives the impression of a Mode III-like crack propagation. Thus, a macroscopic Mode III growth of only partially microscopically tortuous crack front can be produced using this model.

Particle Assisted Growth of Microscopically Straight Crack Front

Even a microscopically straight crack front can propagate in a macroscopically pure Mode III when considering the assistance of cracks related to secondary phase particles, i.e. by fracture of particles or the crack initiation at the particle-matrix interface [14]. A possible micromechanism of straight crack front propagation without any Mode III contributions is schematically drawn in Fig. 4. This idea was already applied to quantitative elucidation of an extremely slow crack growth rate under a macroscopic Mode III (torsion) loading observed in low alloy steels [3,5]. The mean crack propagation rate in such a model depends on the ratio of the length of the microscopic Mode II crack front to the length of the Mode III crack front.

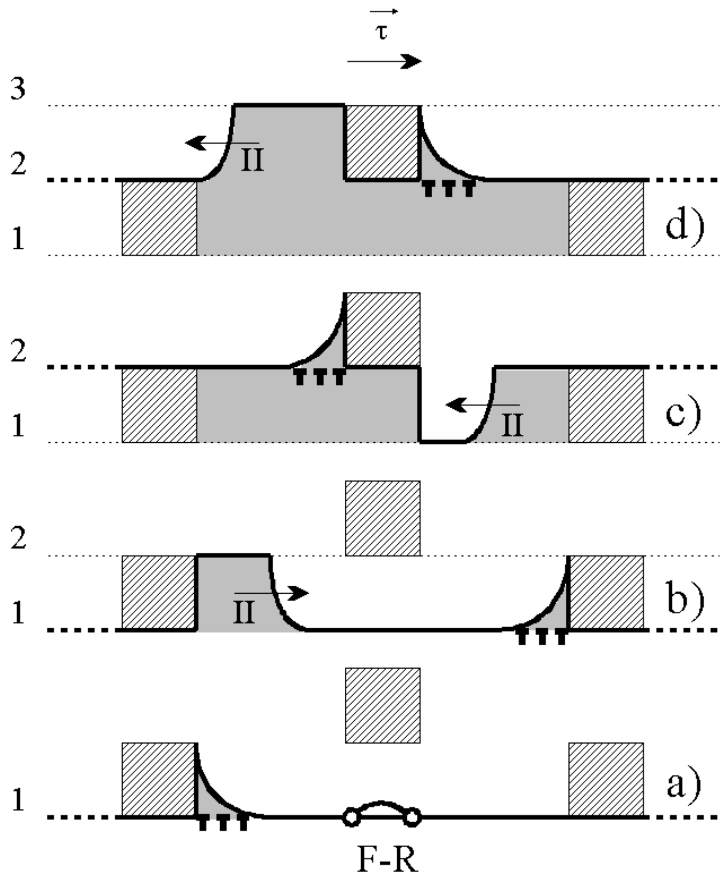

Figure 4. Scheme of a Mode II mechanism leading to a “macroscopic” Mode III crack advance (gray areas) between secondary phase particles (hatched squares),where fracture of the particle-matrix interface is assumed when the crack front approaching the particles.

SOME FRACTOGRAPHIC OBSERVATIONS

Initiation and propagation of fatigue surface cracks in smooth cylindrical specimens made from a low alloy steel were investigated by means of optical and scanning electron microscopes. Pure torsion fatigue tests ($N_f \approx 10^4 \div 10^6$ cycles) were interrupted after defined numbers of cycles and, after a static fracture in liquid nitrogen, both specimen surfaces and fracture surfaces were analyzed. Detected was the formation of a network of microcracks perpendicular and parallel to the specimen axis, covering the whole surface, followed by a coalescence of primarily perpendicular microcracks. A typical shape of an individual microcrack is shown in Fig. 5. A stage I part of the crack exhibits a microscopically rough zig-zag front, very similar to the scheme in Fig. 2. The crack plane has an inclination angle of 45^0 to the macroscopic fracture surface that is perpendicular to the specimen axis. The depth of stage I cracks was in the range of about $10 \div 30$ µm. The stage II part of the crack is inclined of 50^0 to the opposite direction and twisted of 20^0 in order to get a Mode I support. As a rule, the stage II

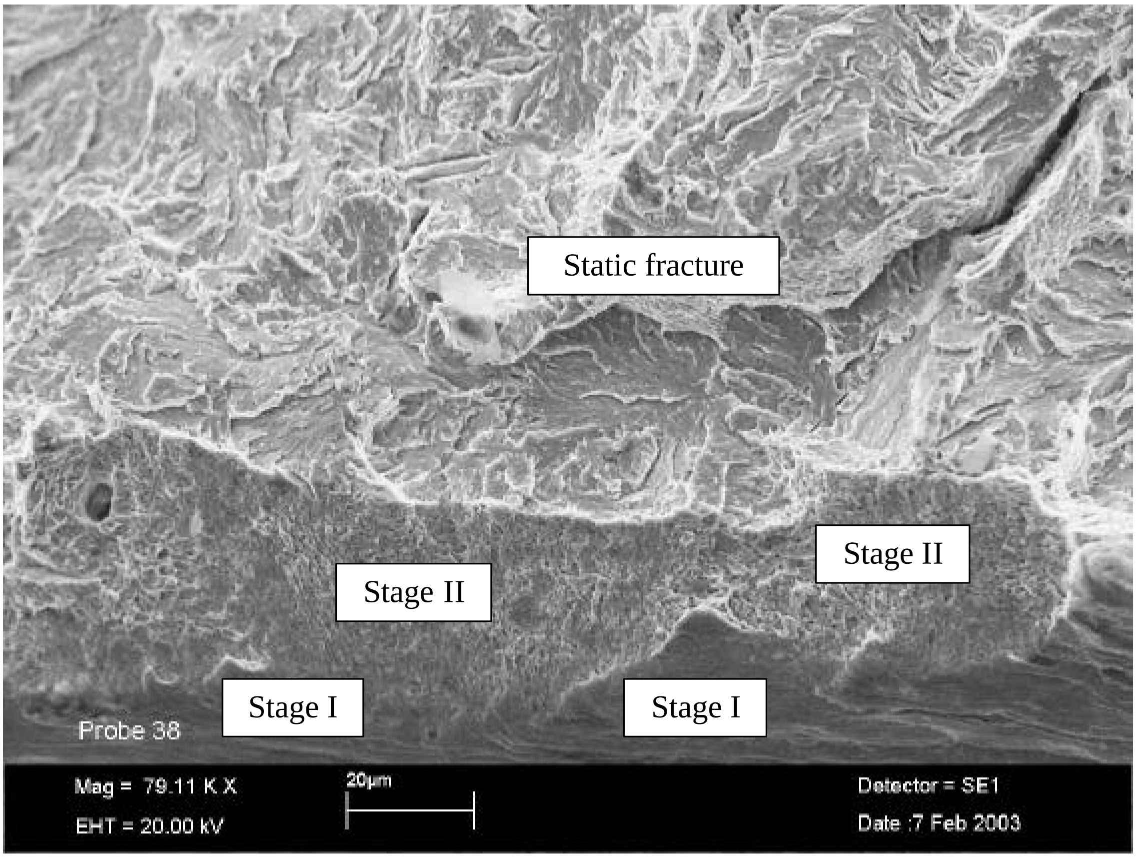

Figure 5. SEM picture of a typical fatigue microcrack developed under pure cyclic torsion on the surface of a smooth cylindrical specimen

crack fronts were smoother than those of stage I. All such cracks were propagating in a Mode I+III to a depth of nearly 100 μm while simultaneously growing and coalescing in Modes II or I+II along the specimen surface. As a result, a shallow circumferential macrocrack has developed round the whole specimen as depicted in Fig. 6. It implies a much higher growth rate of a Mode II or I+II crack front segments in comparison with those of the Mode I+III. This crack growth rate difference, however, should be partially attributed to the coalescence of surface microcracks. In some cases, long Mode I branches were observed leading to a deeper, extremely tortuous surface macrocrack propagating into the interior of the specimen along planes of maximum tensile stress.

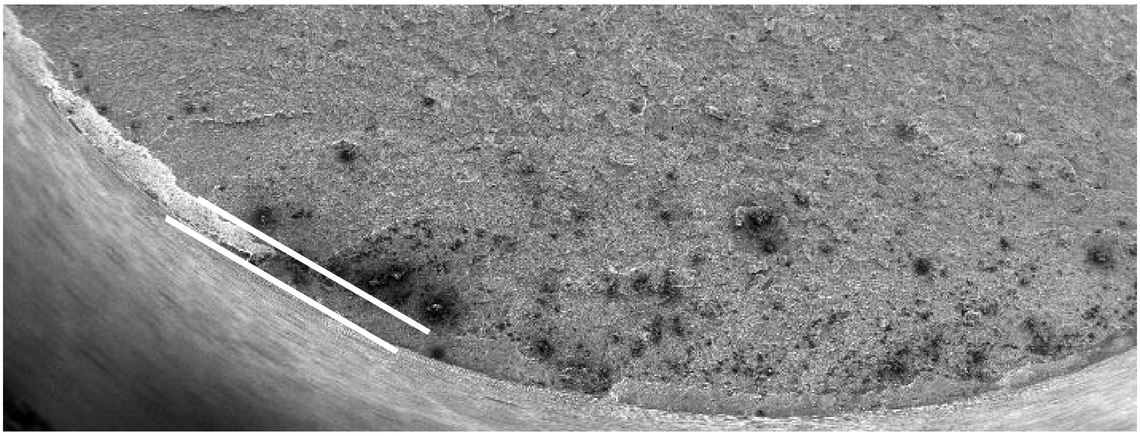

Figure 6. SEM picture of a circumferential crack developed after coalescence of surface microcracks in Modes II or I +II (depth about 100 μm). White lines mark a segment of the continuous fatigue crack.

In general, the fractographic analysis revealed that:

(i) Mode III crack growth was always supported by a Mode I component due to the propagation in planes nearly perpendicular to the maximum tensile stress (short stage I cracks) or even with additional twisting of the crack plane (stage II cracks).

(ii) The Mode II (or I+II) crack growth rate was much higher than that of the Mode I+III which often resulted in a continuous circumferential crack.

CONCLUSION

Most crack configurations lead to a microscopically mixed-mode crack growth. This was already experimentally proved in a sufficient manner and, after all, the above fractographic results confirm this statement. From a microscopic point of view, the occurrence of pure Mode III crack front segments seems also to be highly improbable in heterogeneous engineering metallic materials. Moreover, a pure Mode III crack propagation does not appear to have a plausible support from a theoretical point of view. To some extend, very low Mode III fatigue crack growth rates in comparison with those under Modes I and II are in contradiction with the experimentally found identity of Mode II and Mode III thresholds (and only somewhat lower Mode I threshold) in low carbon steel [8]. However, the latter phenomenon is rather consistent with the proposed alternating Mode II crack propagation model. Also the fractographic Mode III-like features are not conclusive since they can be produced by combined Mode II micromechnisms or even by a pure Mode II propagation leaving the fibrous patterns parallel to the assumed “Mode III” crack front. Therefore, we still do not see any serious indication of a pure Mode III fatigue crack growth in metallic materials hitherto.

Either a very sophisticated *in situ* microscopic observation of a shear crack in the bulk or a pure Mode III loading of a microscopically straight crack front would, most probably, give a satisfactory answer to the question raised in the title of this paper. However, such experiments constitute very difficult tasks.

REFERENCES

1. Pook, L. P. (2002) *Crack Paths,* Wit Press, London.
2. Tschegg, E. K. (1982) *Mater. Sci. Eng.* **54**, 127-136.
3. Ritchie, R. O., McClintock, F. A., Nayeb-Hashemi, H. and Ritter, M. A. (1882) *Met. Trans.* **13A**, 101-110.
4. Tschegg, E. K. (1983) *J. Mater. Science* **18**, 1604-14.
5. Nayeb-Hashemi H., McClintock, F. A. and Ritchie, R. O. (1983) *Int. J. Fracture* **23**, 163-85.
6. Tanaka, K., Akinawa, Y. and Yu, H. (1999) In: *Mixed-Mode Crack Behaviour,* pp. 295-311, K. J. Miller and D. L. McDowel (EDs.), ASTM 1359, West Conshohocken, PA.
7. Tschegg, E. K. (1983) *Acta Metall.* **31**, 1323-30.
8. Murakami, Y., Kusumoto, R. and.Takahashi, K. (2002) In: *Fracture Mechanics Beyond 2000 (ECF 14),* pp. 493-500, A. Neimitz (Ed.), EMAS, U.K.
9. Laird, C. (1967) In: *Fatigue Crack Propagation*, Special Technical Propagation 415, pp.131-68. Philadelphia : The American Society for Testing and Materials.
10. Pelloux, R.M.N. (1969) *Transactions of the American Society for Metals* 62, pp.281-285.
11. Neumann, P. (1969) *Acta Metallurgica* 17, 1219-1225.
12. Murakami, Y. (2001) *Stress Intensity Factors Handbook,* Vol. 4., Elsevier Science Ltd., U.K.
13. Murakami, Y. (2000) Research Report, Kyushu University, Fukuoka.
14. Fine, M. E. and Yip-Wah Chung, R. R. (1996) In: *ASM Handbook - Fatigue and Fracture*, S. pp. 60-72, Lampman (Ed.), ASM International, Materials Park, Ohio.