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Measurements of strain fields around crack tips under proportional and non-proportional mixed-mode fatigue loading

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ABSTRACT

For various configurations examined in a series of fatigue experiments on thin-walled tubes under tension and torsion, the experimental results – crack path, crack growth life, near crack tip deformations, and crack closure – are measured. Optical inspections and digital image correlation technique were used in the experimental investigation. Crack opening and closure loads were determined. The mechanical material behavior has been assumed as linear elastic in a first approach for calculating stress intensity factors. The non-linear nature of the cyclic deformation has been determined experimentally for future use in a cyclic plasticity model.

1. Introduction

The fatigue crack growth under non-proportional mixed-mode loading depends on many influence factors. In a recently published review [1] seven such essential variables have been listed. Firstly, the mode-mixity certainly has an effect on fatigue crack growth. The majority of experimental results – comprehensive compilations can be found in references [2–4] – show a crack turning or kinking towards a path minimizing mode II states which may be well described by the maximum tangential stress criterion. However, Roberts and Kibler [5] found cases for which the maximum tangential stress criterion was not valid. They produced conventional fatigue cracks under mode I loading. Then Mode II was applied. Under high mode II amplitudes the crack did not kink but continued to grow in its original direction, now under mode II. Only the maximum shear stress criterion can model this behavior. This means that increasing mode-mixity creates a tendency for a shear dominated crack growth instead of a tensile stress dominated one, the latter being the usual case. Secondly, fatigue crack growth paths depend on the material. Qian and Fatemi [2] conclude that “mode II crack growth occurs more often in aluminum alloys than in steels”. A correlation with the material strength is found in a way that the tendency towards a shear dominated crack growth increases with decreasing strength. However, no clear classification exists which materials under which conditions show preferred affinity to a shear-including growth. The third influence factor is the magnitude of cyclic plastic deformation. With increasing cyclic plastic deformation the shear dominated fatigue crack growth becomes more important. Early results by Tanaka [6] were followed by confirming these findings published e.g. by Brown and Miller [7], Otsuka and Tohgo [8], Socie [9], or Doquet and Bertlino [10]. The cyclic plastic deformation is also the origin of the fourth influence factor: crack closure. Especially in non-proportional cases, the roughness and friction induced crack closure occurs and interacts with the plasticity induced crack closure. An interlocking of the crack flanks due to roughness induced crack closure leads to a crack tip shielding of the mode II component. This phenomenon is especially observed for low stress intensity factor ranges. For large ranges, however, friction and wear of the crack flanks together with plastic deformations at the fracture surface may remove the roughness induced crack closure and with it the mode II shielding. Crack closure and mean stress effect – the fifth influence factor – are closely related phenomena and therefore all effects should be discussed against the background of the effect of the mean stress. Moreover, the geometry of a structure – the sixth variable – may force a fatigue crack to develop a fracture surface under large mixed-mode conditions, e.g. a notched shaft under torsion. Finally, in three-dimensional structures the mode-mixity is generally changing along the crack front. The direction of the crack growth increment along the crack front, according to a criterion identified under plane stress or strain conditions, might lead to incompatible crack surface geometries [3]. Several facets of individually growing cracks may develop along an originally

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Nomenclature

a	crack length	N	number of cycles to failure
E	Young's modulus	r	radial distance in polar coordinate system
F	force	R	stress ratio
i	counter	v	displacement
J	J-integral	x	coordinate
K	stress intensity factor	Y	geometry influence function
K'	cyclic hardening coefficient	δ_t	crack tip opening displacement
m	exponent in crack growth law	ε	strain
M	moment, torsion	σ	stress
n	number of applied load cycles	θ	angle in polar coordinate system
n'	cyclic hardening exponent		

continuous crack front. After the rupture of the ligaments, between the facets, a stepped and jagged crack surface might evolve. These seven influence factors are closely interrelated, therefore a study of individual factors is hard to achieve.

The additional difficulty in modeling fatigue crack growth under mixed-mode loading is determining the direction of the growth increment. Simulations are concentrated on two main alternatives: the crack is supposed to minimize either shear modes II and III or opening mode I when finding its path through the structure. Minimizing the shear modes is preferred by a variety of mixed-mode criteria, e.g. if a tensile circumferential (tangential) stress [11] or strain [12] in the perimeter of the crack front field is declared decisive for the growth direction. Along the perimeter, during non-proportional mixed-mode loading, the location of the maximum of this variable is changing. Currently, it is even not clear, whether the maximum value or the maximum range of the variable (or both, see [3]) indicate the direction. Shear-modes minimizing results are also obtained by applying some energy [13] or energy release rate [14] based criteria. In contrast, the crack geometries maximizing shear modes are obtained by applying the maximum shear stress criterion [15]. The same questions are open whether to rely on quantities calculated with linear elasticity theory or including plasticity and whether ranges or peak values during a cycle are decisive. Such alternative crack paths can be derived following ideas of Gao et al. [16] who link the geometry of the "true plastic zone size" to direction and rate of fatigue crack growth. The J-integral criterion [17] and its cyclic counterpart, the ΔJ-integral, which have also been proposed, may be used to create an opportunity for directing the modeled crack increment to the experimentally observed orientation. The ΔJ-integral must be understood according to the definitions by Dowling and Begley [18], Wüthrich [19], and Hertel et al. [20]. This optimistic assumption is due to the ΔJ-approach's success in modeling short crack growth under proportional and non-proportional loading conditions [21–25]. However, short cracks usually are growing in a (critical) plane with negligible curvature and kinks. This simplifies modeling to an iterative search for this plane. It has been argued by Hoshide and Socie [21] that the fatigue crack growth rate should be correlated with the crack tip displacements. They used the ΔJ-integral as a substitute for the crack tip opening displacement, δ_t, due to the difficulty of measurements. Nevertheless, Li [26] proposed a criterion based on the vector sum of crack tip opening and sliding displacement. He reported good agreements between his numerically and Yokobori's et al. [27] experimentally obtained results. In the current investigation, the digital image correlation (DIC) technique was applied which offers a new opportunity for measuring crack opening displacements. It is in the nature of these measurements, that the effect of crack closure was taken into account. Under mixed-mode loading, the roughness-induced closure becomes more important. While Döring et al. [23] applied an empirical equation for taking crack surface friction into account for short cracks, the associated problem for long cracks is examined by Dahlin and Olsson [28] as well as Gates and Fatemi [29].

A research project was launched, seeking further knowledge on the mechanisms. Results achieved so far are the subject of this paper. This investigation focused on high amplitude loading accompanied by large cyclic plastic deformation, high crack growth rates, and short fatigue lives. Only naturally initiated fatigue cracks are in the scope of this work. Fatigue life assessment methods for initiation of cracks are available even for the non-proportional cases of combined cyclic loading. Although their accuracy is under discussion, engineers are backed by helpful numerical tools. However, investigations concerning the fatigue crack growth stage are still rare. In the present study, path and rate of such cracks as well as displacement and strain field around the crack tip area were observed experimentally when growing out of the notch into a field imposing mixed-mode loading at the crack front. Two different experimental setups were used for this purpose: crack path and crack growth were examined using optical measurements made with three cameras. Displacement and strain fields were determined using the digital image correlation technique (DIC). The deformation of the structure in the crack tip environment was measured. Access to information on crack closure and mixed-mode crack opening displacements was acquired. In order to connect the results to the state of the art, the experimental methods are first applied to cases with proportional loading. In a series of experiments the tests were occasionally interrupted and the deformation field was measured applying the 3D-DIC technique. This technique gains growing interest in measuring materials' mechanical deformation. It allows for measurements of the strain fields also in the vicinity of crack tips [30]. The use of digital image correlation (DIC) to determine fracture parameters was earlier proposed by McNeill et al. [31,32] and more recently by Yoneyama and Murasawa [33]. In Ref. [32] the DIC displacement full-field data was fitted, using the least square technique, to the Westergaard solution [34] for a cracked body problem. In that paper [33] the authors determined not only mode I stress intensity factors (SIFs) but also rigid body motion and other far field parameters of the truncated series-type stress function used in the solution. More recently the integral J was evaluated using the DIC technique [35]. Not only opening mode I but also mode I and mode II SIFs can be determined using DIC, even for complex geometries. An example of mixed-mode I and II SIF calculation using DIC in an aluminum plate mounted in an Arcan loading fixture is presented by Zhang and He in [36]. Shukla and Dally [37] and Sanford [38] present infinite series stress functions proposed by Westergaard and by Williams that form the theoretical basis for mode I and mode II SIF determinations using experimental techniques.

Based on these results, ideas are presented which are intended to describe the fatigue crack growth behavior observed in the