ON THE INFLUENCE OF HIGHER ORDER TERMS Of THE STRESS FIELD EQUATIONS IN TRANSIENT FRACTURE PROBLEMS

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For dynamic fracture problems influences of far field effects due to higher order transient terms on the determination of dynamic stress intensity factors from direct measurements of the crack tip stress field are investigated by means of the shadow optical method of caustics using a dual-focus high-speed-camera. The effects are found small for loading rates of practical relevance, contrary to results reported by Rosakis. The large effects observed in those investigations are attributed to disturbing plasticity effects.

INTRODUCTION

The determination of fracture mechanics parameters, i.e. stress intensity factors or J-Integral-values from direct measurements of the crack tip stress field by means of experimental methods, such as strain gauge techniques, photoelasticity, caustics, etc. requires an evaluation of data that - by necessity - are recorded at some finite distance from the crack tip. Consequently, far field effects of the crack tip stress field in the form of higher order terms (Williams solution (1)) must principially be taken into account with such procedures: the higher order terms can only be neglected if their magnitude has been proven to be sufficiently small.

For the investigation of dynamic fracture problems, e.g. propagating cracks or cracks under impact loading the situation becomes more complex: elastic waves as the carrier of information of transient stress fields require finite times to travel finite distances. Consequences on the significance and the interpretation of experimentally determined fracture mechanics parameters due to these

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finite information times are illustrated in Fig. 1 using a simplifying model based on characteristic delay times. Since complete solutions of transient fracture problems including time dependent higher order terms became available only recently by work of Freund (2) far field effects in dynamic fracture problems could not exactly be taken into account: the effects were certainly minimized by choosing small measuring distances but at the end they had to be neglected. This paper is aimed to quantify influences of dynamic higher order transient effects for fracture problems of practical relevance, in particular in view of recent investigations by Rosakis (3) with the same intention.

DETERMINATION OF FRACTURE MECHANICS PARAMETERS FROM STRESS VALUES AT DIFFERENT DISTANCES FROM THE CRACK TIP

Although effects due to higher order transient terms and finite measuring distances apply to any experimental technique for determining fracture mechanics parameters the shadow optical method of caustics is used here for quantifying these effects. For a description of the basic principles and the theoretical background of the shadow optical method of caustics the reader is referred to a review article of the author (4). As schematically shown in Fig. 2 a caustic recorded at a distance z_{0B} behind the specimen is formed by stresses at a distance r_{0B} from the crack tip, whereas a caustic for a smaller distance z_{0A} is formed by stresses at a smaller distance r_{0A}, $r_{0A} < r_{0B}$. Thus, by varying the distance z_0 in a shadow optical arrangement stress intensity factors can be determined which are formed by stress values which apply for different distances from the crack tip. For these investigations two caustics of a dynamic fracture event are recorded in two reference distances z_{0A} and z_{0B} with a Dual-Focus Cranz Schardin High-Speed-Camera: Two photographic films with different effective distances to the photographic lens, thus focussing different image planes, are exposed simultaneously via a partial mirror arrangement.

EXPERIMENTAL RESULTS

With a shadow optical arrangement similar to the one described above Rosakis (3) determined stress intensity factors for cracks under impact loading conditions. Three point bend specimens of 300 mm length, 127 mm width, and 10 mm thickness made from the high strength steel 4340 (quenched and tempered, $\sigma_Y \approx 1400$ MN/m²) with saw cuts of 38 mm length (simulating the initial crack) were loaded in a drop weight tower at impact velocities of a few m/s. The r_0-values were varied by 20%, with all r_0-values lying outside the three dimensional crack tip stress field region, $r_0 \geq h/2$, where h = thickness of the specimen. Differences in the stress intensity factors by as much as 60% were obtained when an evaluation procedure was used which was based on the near field first order stress term. Rosakis (3) speculates that this discrepancy is due to the neglected higher order transient terms of the stress field.

In order to check this observation similar experiments were carried out by the authors with specimens 412 mm long, 100 mm wide, 10 mm thick prepared with saw cuts of 50 mm length and impacted at 0.3 m/s to 5 m/s. In order to avoid any kind of disturbances due to other effects, e.g. due to local plasticity at the crack tip, the specimens were made from a model material, the epoxy resin Araldite B, which shows an almost ideal linear-elastic behaviour up to fracture. The results are shown in Figs. 3 and 4. The experiments reported in Fig. 3 were performed applying the shadow optical method in transmission, the experiments at lower impact velocities (Fig. 3a,b) did not lead to fracture (undercritical experiments), the experiment performed at 5 m/s (Fig. 3c) resulted in complete failure of the specimen (overcritical experiment). Figure 4 shows results obtained by applying the shadow optical method of caustics in reflection with a specimen that was specially prepared with a mirrored front surface. The distances z_0 were varied in the range from 1.4 m to 2.1 m. Since r_0 in addition to z_0 also depends on the stress intensity factor value (see (4)) the resulting r_0-values for each experiment varied over a certain range given in the individual figures. In all cases special efforts were made that r_0 was sufficiently large, $r_0/h \geq 0.5$, i.e. that stresses outside the three dimensional stress field region around the crack tip were considered.

With the undercritical experiments variations in r_0 by 24%/38% resulted in an average variation of the stress intensity factors of 2.0%/1.9%, with the overcritical experiment a variation in r_0 by 30% resulted in an average variation of the stress intensity factors by 3.5%. With the reflection experiment, for a variation in r_0 by 22% an average variation in the stress intensity factors by 6.1% was obtained. Shadow optical reflection data because of higher requirements on the precision of the experimental arrangement generally show a larger scatter than data obtained in transmission arrangements.

DISCUSSION OF EXPERIMENTAL DATA

In the presented experiments the r_0-variations were considerably larger (up to 38%) than the variations in the experiments of Rosakis (only 20%), nevertheless, the variations in the stress intensity factors were only a few percent and thus considerably smaller (by more than a factor of 10) than the 60% variations reported by Rosakis. Thus, the influences of higher order transient terms are obviously considerably smaller than originally speculated by Rosakis.

An explanation for this behaviour results from a consideration of the caustic patterns obtained by Rosakis: Figure 5 shows the two caustics recorded at different z_0-distances for a stationary crack subjected to impact loading (Fig. 5a) and for a propagating crack (Fig. 5b). Due to experimental reasons the two caustics in Rosakis' experiments are recorded on the same photographic film. Whereas the caustics for the impacted stationary crack exhibit the usual shape, the caustics for the propagating crack show disturbances: in particular the stress free fracture surfaces behind the crack tip generate a large shadow optical effect which obviously is caused by the plastic wake formed by the plastic zone at the tip of the propagating crack. Thus, the caustic at the crack tip is only to a certain minor part generated by the elastic crack tip stress field, i.e. the stress intensity factor, and to a larger part generated by plasticity effects. An evaluation of such caustics on the basis of linear-elastic analyses, consequently, must result in erroneous data. Whereas this problem is clearly visible for the propagating crack it can easily be overlooked in the equivalent experiments of impacted stationary cracks if an additional independent check on the applicability of a linear-elastic evaluation procedure is not performed. In order to avoid difficulties of this kind the author and his colleagues in their previous work in investigating dynamic fracture problems by means of the shadow optical method of caustics (5) used the high strength maraging steel X2 NiCoMo 18 9 5 with a yield strength of $\sigma_Y \approx 2100$ MN/m^2 which is considerably larger than the yield strength of the steel 4340 used by Rosakis.

It is concluded, therefore, that the large discrepancies in the determination of dynamic stress intensity factors reported by Rosakis are not due to higher order transient effects but due to a non valid application of a linear-elastic evaluation procedure to measuring signals that are heavily disturbed by plasticity effects. For loading rates of practical relevance influences due to higher order transient terms of the crack tip stress field obviously are small and can be neglected for engineering purposes if the necessary precautions in the generation of the data and their evaluation are fulfilled.

REFERENCES

(1) Williams, M.L., "On the Stress Distribution at the Base of a Stationary Crack", J. Appl. Mech. 24, 1957, 109-114

(2) Freund, L.B., "Dynamic Fracture Mechanics", Cambridge University Press, Cambridge, 1990

(3) Krishnaswamy, S., Rosakis, A.J., "On the Extent of Dominance of Asymptotic Elastodynamic Crack-Tip Fields; Part I: An Experimental Study Using Bifocal Caustics", J. Appl. Mech. 58, 1991, 87-94

(4) Kalthoff, J.F., "Shadow Optical Method of Caustics", Chapter 9 in "Handbook on Experimental Mechanics", Ed. A.S. Kobayashi, Prentice Hall, Englewood Cliffs, New Jersey, 1987, 430-500

(5) Kalthoff, J.F., "Experimental Fracture Dynamics", in "Crack Dynamics in Metallic Materials", CISM Book 310, Ed. J.R. Klepaczko, Springer-Verlag, Wien, New York, 1990, 69-253

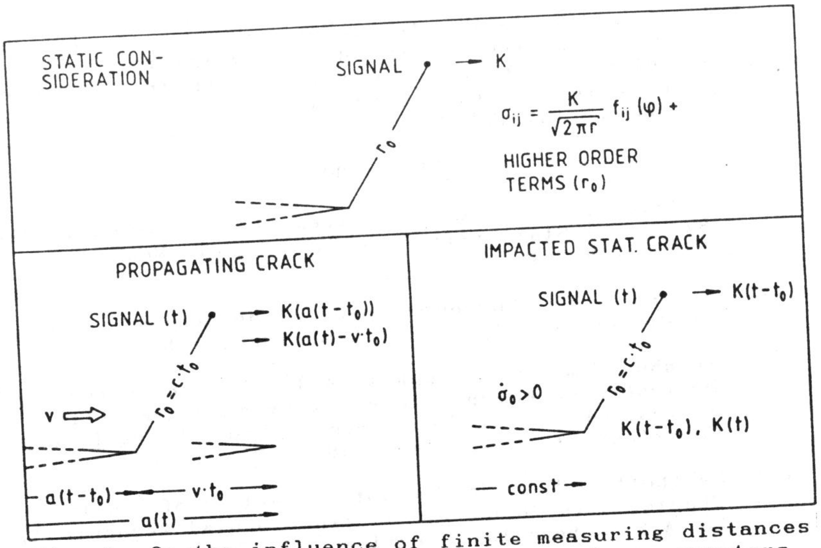

Fig. 1 On the influence of finite measuring distances for determining fracture mechanics parameters

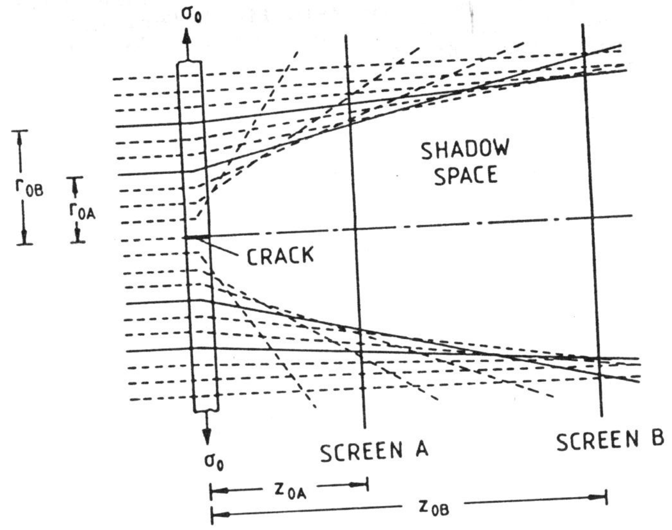

Fig. 2 On the generation of caustics by stress values of different crack tip distances

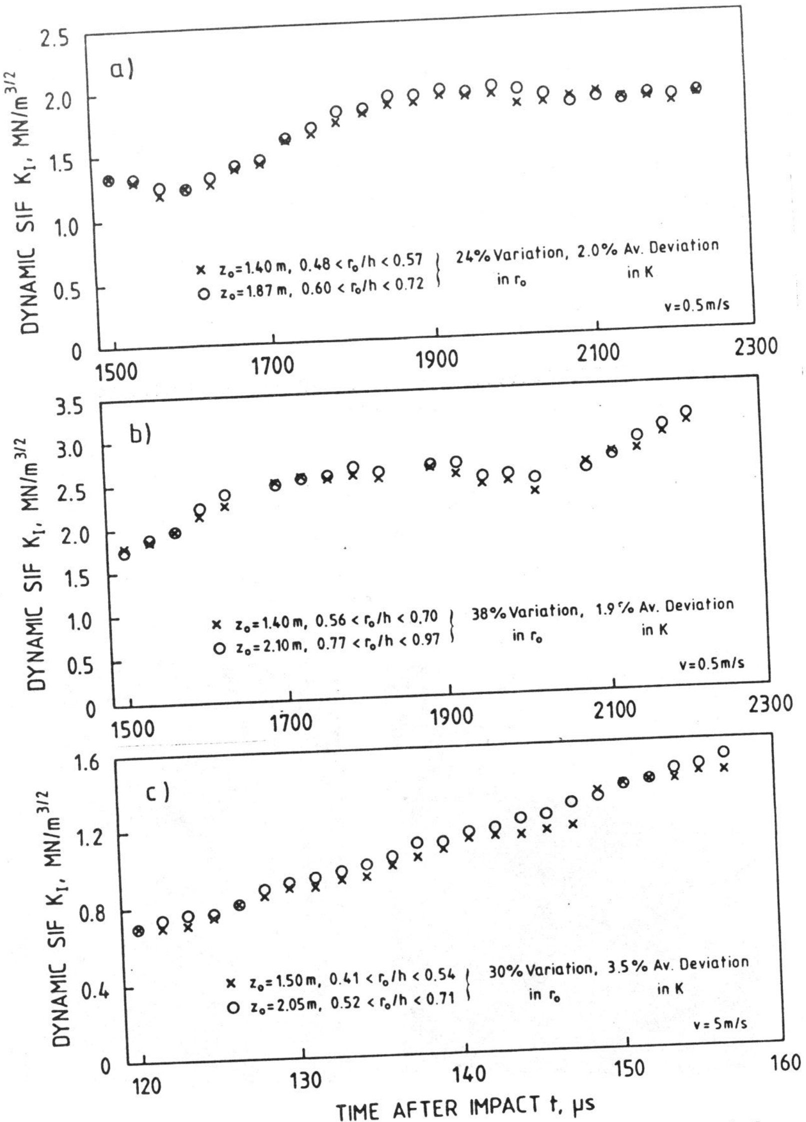

Fig. 3 Dynamic stress intensity factors obtained from stress values of different crack tip distances (shadow optical transmission arrangement)

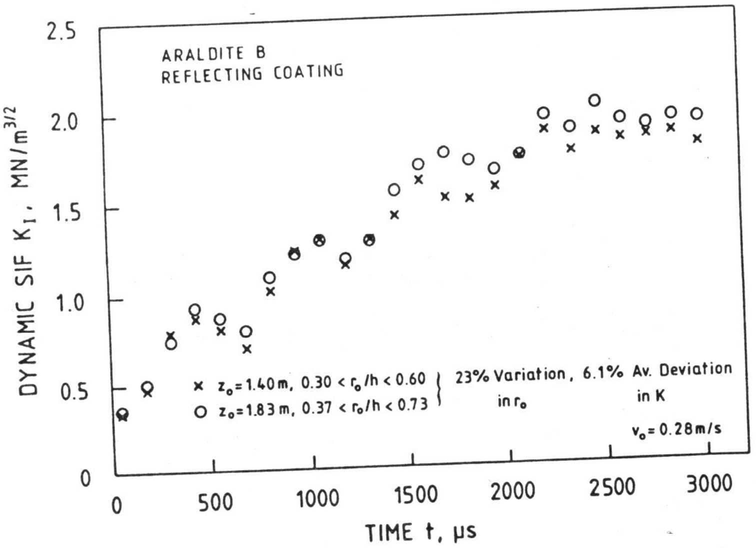

Fig. 4 Dynamic stress intensity factors obtained from stress values of different crack tip distances (shadow optical reflection arrangement)

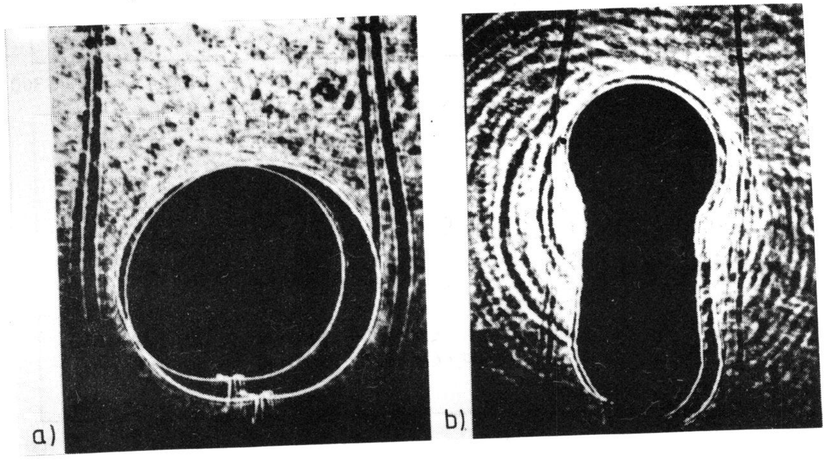

Fig. 5 Caustic patterns after Rosakis (3) for
a) a stationary crack under impact loading and
b) a propagating crack