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J-INTEGRAL AND HRR FIELD OF A STABLY GROWING CRACK, AN EXPERIMENTAL ANALYSIS

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J-INTEGRAL AND HRR FIELD OF A STABLY GROWING CRACK, AN EXPERIMENTAL ANALYSIS

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SUMMARY

The displacement fields surrounding stably growing cracks in 7075-T6, 2024-0, 2024-T3, 5052-H32 and 2091 aluminum alloy, standard and cruciform, single-edge notched (SEN) specimens were determined by Moire interferometry. An approximate and exact J-integral values were determined and found to be within 5% of each other and were both path independent. The associated HRR crack tip displacements in all specimens were in agreement with the measured displacements vertical to the crack but consistently differed in magnitude and order of singularity with the measured displacements parallel to the crack.

INTRODUCTION

One of the most popular ductile fracture criterion of the past two decades is the J-integral concept [1] for which enormous developmental efforts have been expended in recent years. The J-integral is heralded by many as a stable crack growth and ductile fracture criteria since in its linearly elastic limit, it reduces to the elastic strain energy release rate. The path independency of the J-integral also provides the experimentalist with the convenience of determining the potential energy change due to an incremental crack extension by far field measurements. In addition, if one postulates a power hardening material and the existence of a HRR field [2,3], the crack tip state can then be charactrized by the J-integral. Such convenience prompted the use of J-integral for correlating fatigue, creep and stable crack growth data in addition to its role of quantifying the onset of ductile fracture. The inherent unloading process associated with crack growth in ductile material, however, violates the postulate of nonlinear elasticity on which the J-integral is founded [1]. Extensive numerical analyses [4-6], showed that the J-integral is still a viable far-field parameter for determining the potential energy change under small crack extension and that the HRR field is a reasonable representation of the crack tip state. Unfortunately, no comparable experimental analysis of the above, with the exception of [7] and those of the authors, exists to date. The purpose of this study is to provide the missing experimental verifications of the path independency of the J-integral and of the existence of a HRR field.

J-DETERMINATION PROCEDURE

Approximate J-integral

The J-estimation procedure consists of approximating the two-dimensional state of stress in the fracture specimen with the uniaxial state of stress where the shear and the lateral normal stresses are considered negligible. For a standard SEN specimen, this replacement provides the exact state along the two lateral boundaries. If the two horizontal paths are sufficiently remote from the crack tip and if the SEN specimen is subjected to a uniform loading, then this replacement provides the exact state. The J evaluated along the most remote contours in the SEN specimen using the J-estimation procedure will then yield the correct J-integral value. Extensive error analysis [8] showed that this estimation procedure provided reasonably accurate J-values for the SEN specimens. This procedure was then used to estimate the J-integral values in subsize 7075-T6, 2024-0 and 5052-H32 aluminum alloy SEN specimens of 0.8 mm thickness [8-10].

Exact J-Integral

The subsequent development of an improved moire interferometry setup, where both the vertical and horizontal displacements could be recorded simultaneously in a single frame [11], provided an improved procedure, which is conducive to high-speed photography, where the exact J-integral value is determined within the confines of the constitutive relation. Details of this procedure, which was used to determine the J-values associated with stable crack growth in large biaxially and uniaxially loaded, 7075-T6, 2024-0, 2024-T3, 5052-H32 and 2091 aluminum alloy, cruciform and standard SEN specimens, 0.8 mm thick, are described in [12-15]. Biaxiality ratios of B = 0.0, 2.0 were applied to the cruciform specimens through a special biaxial testing machine [16] and stable crack growth in excess of 5 mm were obtained prior to rapid tearing. The J-integral values were then evaluated along two or three contours encompassing the crack tip.

RESULTS

Figures 1(a) and 1(b) show a typical moire fringe pattern corresponding to the vertical and horizontal displacements, v and u, in a 2024-0 aluminum specimen. Figures 2(a) and 2(b) show typical plots of v and u versus the radial distance, r, for various angular orientation, θ. For a power hardening coefficient of $n = 4$ of this 2024-0 aluminum alloy, the HRR field predicts a slope of 0.2 in the log-log plots of the v and u versus r curves.

While Figure 2(a) verifies the HRR predicted slope for the v-field, Figure 2(b) shows a measured slope of nearly 0.5 for the u-field. The many log-log plots of all other aluminum alloy specimens, showed that the predicted power of $1/(n+1)$ or r for the HRR crack tip displacement was more or less replicated by the measured v-displacement but the measured u-displacement field consistently indicated a power of 0.5 of the radial distance.

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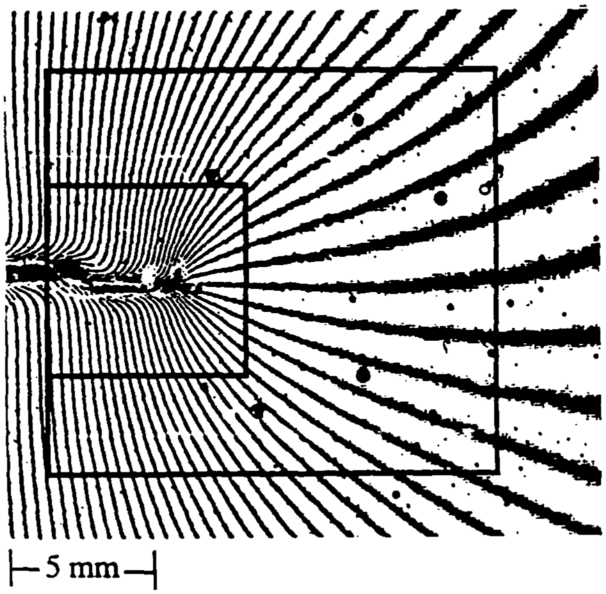

Fig. 1(a) v-Displacement in 2024-0 Al Cruciform Specimen. B=2.0.

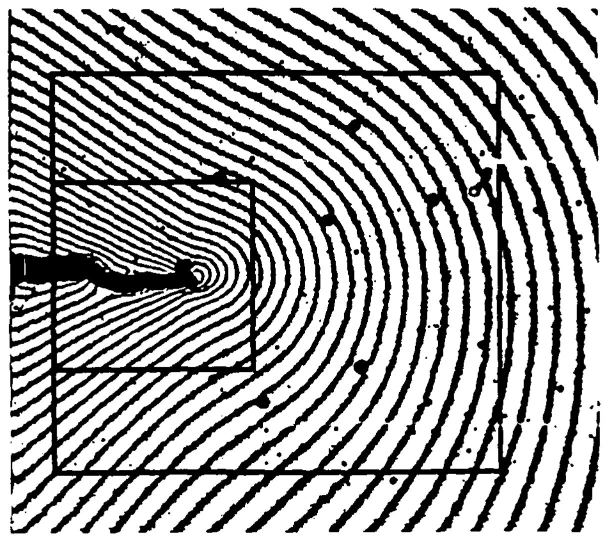

Fig. 1(b) u-Displacement in 2024-0 Al Cruciform Specimen. B=2.0.

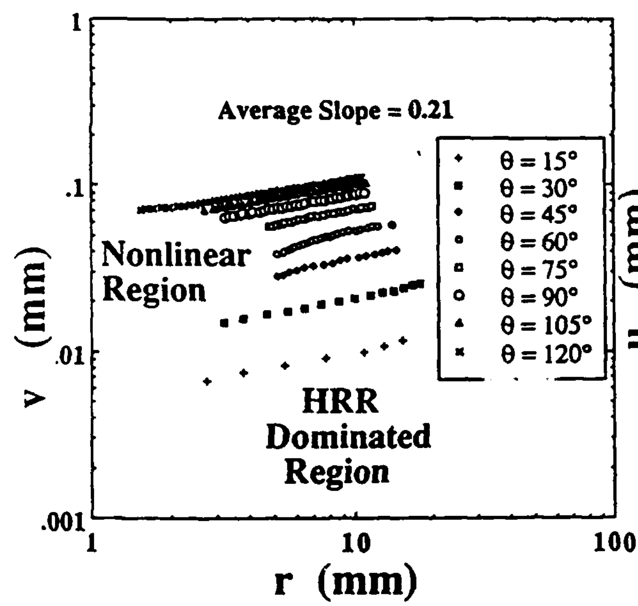

Fig. 2(a) v-Displacement Versus r for Various Angles.
2024-0 Al Cruciform Specimen.

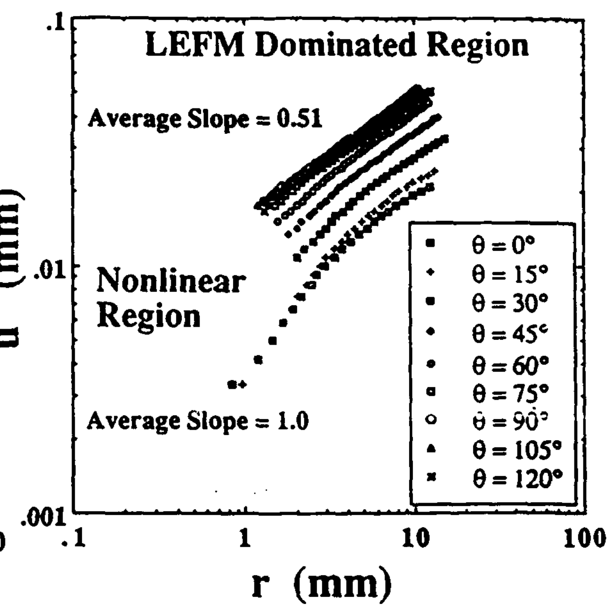

Fig. 2(b) u-Displacement Versus r for Various Angles.
2024-0 Al Cruciform Specimen.

Since the 7075-T6 aluminum standard and cruciform SEN specimens essentially provided an elastic crack tip state, this moire fringe data was used to check the validity of both the estimation and exact procedures for determining J-integral values. In addition, the accuracy of the procedure was verified by computing the J-integral value along a countour. This J-value, which did not enclose the crack tip in a 2024-T3 cruciform specimen, was 0.4 % of the minimum recorded J-value for this specimen for a contour.

Figures 3(a) and 3(b) show typical J_R-curves for uniaxially (B = 0) and biaxially loaded (B = 2) 2024-T3 and 2091-T3 aluminum cruciform specimens, repectively. Despite the maximum differences of 4.4 cm in the lengths of integration paths, the J-values for each crack length differed at the most of 8 percent. The extrapolated J_R-curves inferred a critical J ~ 8 and 10 kPa-m for uniaxially and biaxially loaded specimens, respectively.

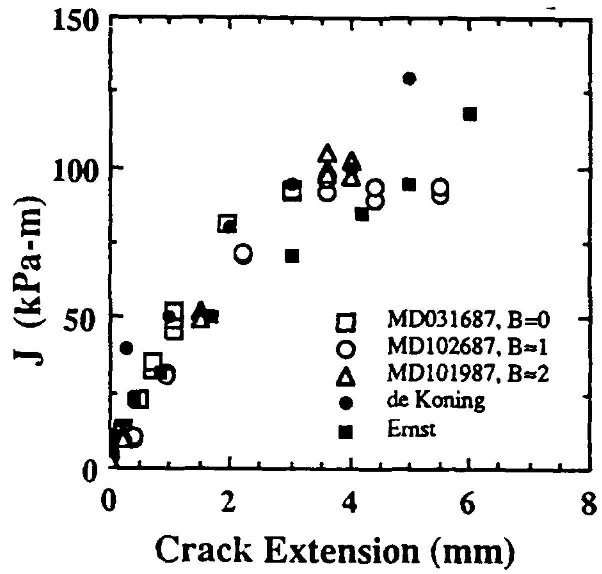

Fig. 3(a) J_R-Curve of 2024-T3 Al Cruciform Specimen.

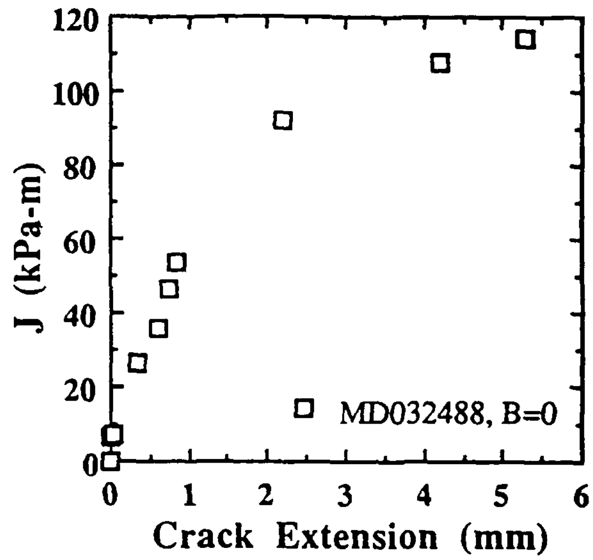

Fig. 3(b) J_R-Curve of 2091-T3 Al Cruciform Specimen. B = 0.

Figure 4(a) shows the J_R-curves for the approximate and exact J-values obtained from 2024-0 small and large SEN specimens, respectively. Figure 4(b) shows similar J_R-curves for 5052-H32 and small SEN and large cruciform specimens.

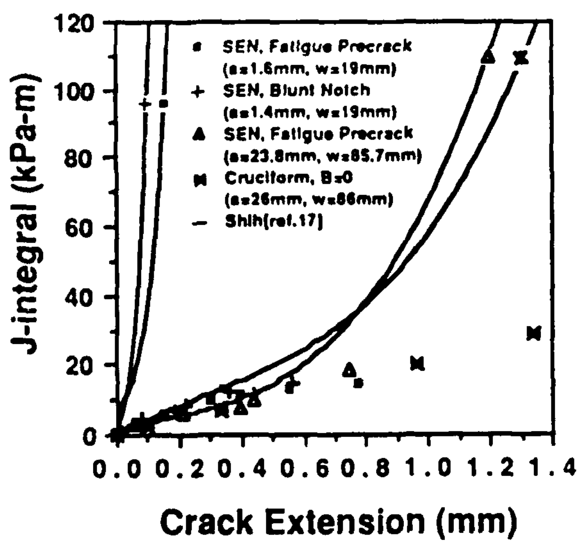

Fig. 4(a) J_R-Curve of 2024-0 Al Small SEN and Large Cruciform Specimen.

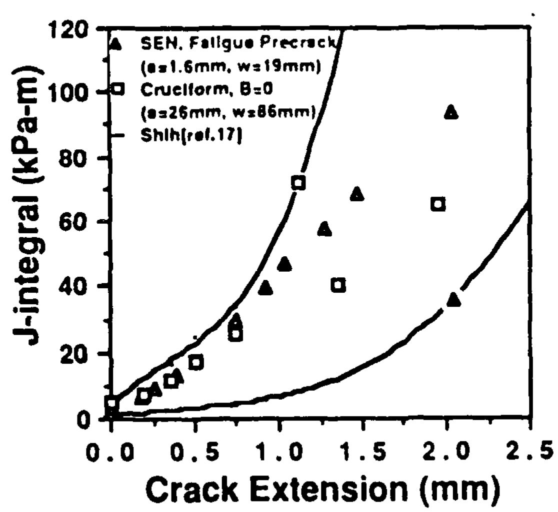

Fig. 4(b) J_R-Curve of 5052-H32 Al Small SEN and Large Cruciform Spec.

Also shown are the J_R-curve predicted by using the J prediction method by Shih [17]. While the Shih's J prediction method was obviously meant for a stationary crack, the predicted J deviated substantially with the measured J values of the SEN specimens as well as at larger crack extension, i.e. Δa > 0.6 ~ 1.0mm, of the large cruciform specimens.

The J-integral values shown in Figures 3 and 4, as well as the many other J-resistance curves, which were generated in the course of this investigation, were used together with the associated power hardening coefficients to evaluate the v- and u-displacements of the HRR field [2,3]. The crack tip displacements for a linearly elastic aluminum SEN specimen was also computed. Figures 5(a) and 5(b) show the measured and the computed HRR and LEFM v- and u-displacement variations, at a radial location of r = 1.2 mm and angular orientation, θ = 45°, from the crack tip, with increasing crack extension in the SEN and the cruciform specimens, respectively. The LEFM component was computed by equating J to the elastic strain energy released rate from which a stress intensity factor was computed. The fitted curves through the measured v- and u-displacement data accentuated the closeness or difference with the computed HRR and the LEFM displacements. The measured v-displacement initially followed the computed LEFM displacement but changed to the corresponding computed HRR component at higher loadings in all four aluminum specimens. The measured u-displacements for the uniaxially and biaxially loaded cruciform specimen, on the other hand, generally followed the corresponding LEFM component.

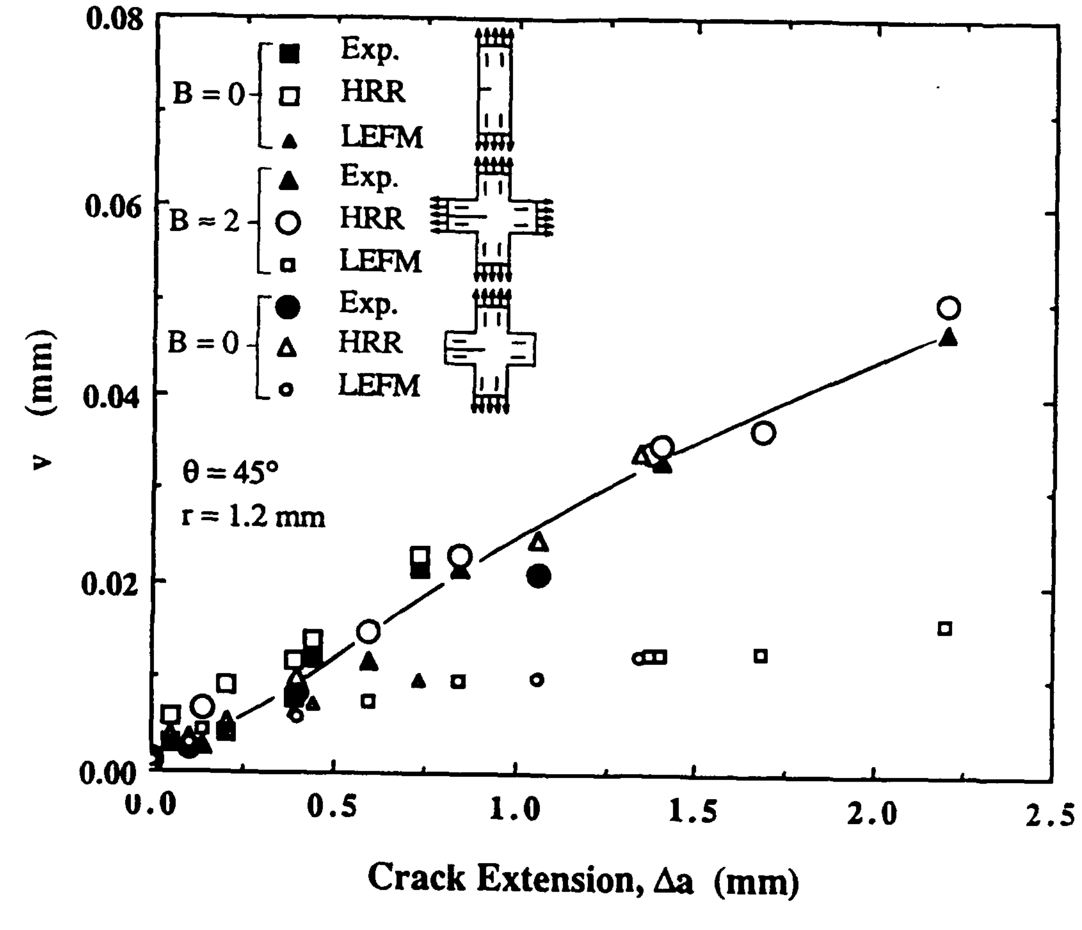

Fig. 5(a) v-Displacement in 2024-0 Al. SEN and Cruciform Specimen.

Similar plots of the v- and u-displacements in 5052-H32 aluminum cruciform specimens are shown in Figures 6(a) and 6(b). Due to the large non-linear zone in this material, the v- and u-displacements were computed at a radial distance of r = 5mm and an angular orientation θ = 45°. Also shown are the u- and v-displacements computed by using the HRR field and LEFM.

CONCLUSIONS

The J-integral values obtained by the approximate and the exact procedures with standard and uniaxially and biaxially loaded standard and cruciform, aluminum SEN specimens were contour independent and essentially vanished for contours not enclosing the crack tip.

The vertical HRR crack tip displacements, v, which were computed by using the J-integral values, agreed reasonably well with the corresponding measured values. The horizontal HRR crack tip displacement, u, essentially followed its LEFM counterpart in all specimens tested. Thus, the HRR field is not a valid representation of plastic crack tip region.

The plastic crack tip region cannot be characterized by the J-integral through the HRR field. Thus J-integral as a ductile fracture criterion lacks physical interpretation at this time.

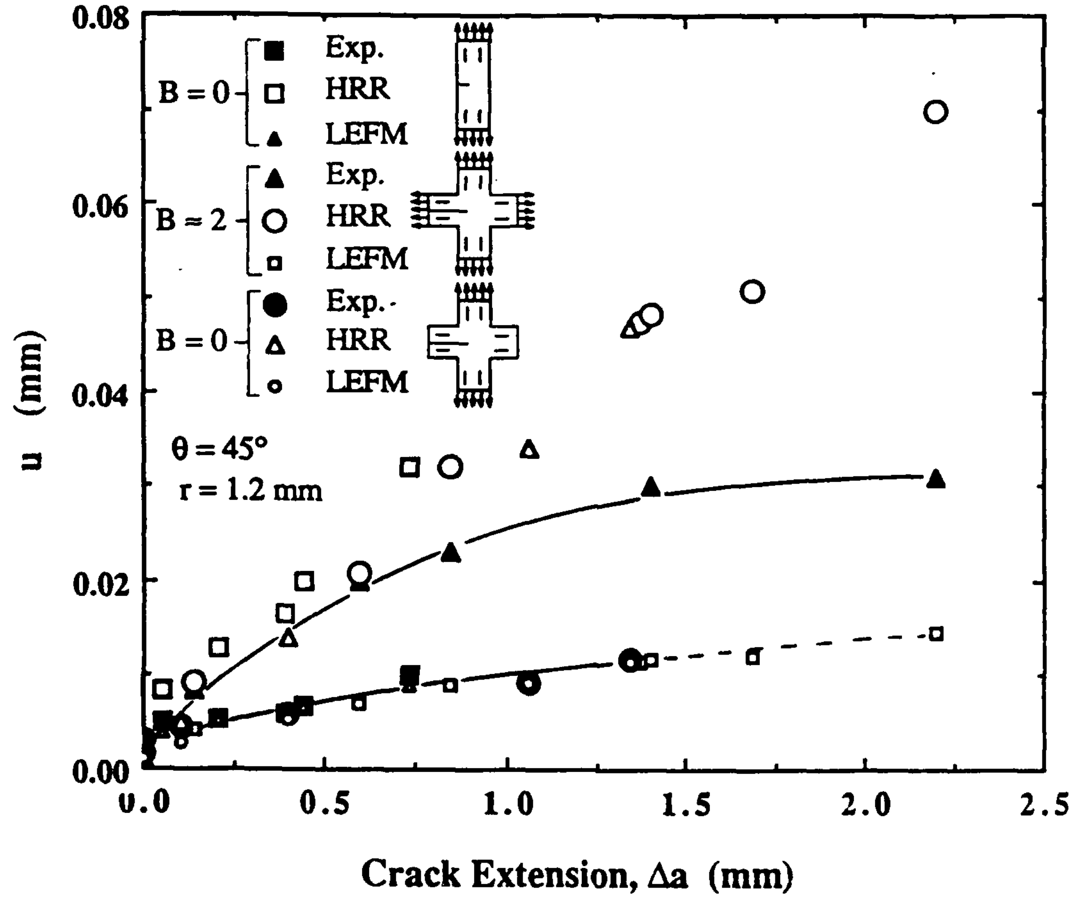

Fig. 5(b) u-Displacement in 2024-0 Al. SEN and Cruciform Specimen.

DISCUSSIONS

The authors were gratified for being the catalyst for a recent numerical analysis of the elastic-plastic crack tip region in which the horizontal displacements, u, were found to vary with $r^{\frac{1}{2}}$ power [17]. It is somewhat ironical that the massive computational efforts in elastic-plastic fracture analysis over the past two decades failed to consider the horizontal crack tip displacement, which was embedded in all computed outputs of the past. Figures 5 and 6 show that the u-displacement is about one third of the dominant v-displacement and is not negligible as considered by some. The authors' studies and the quoted numerical analysis [18] are vivid examples of the danger of accepting theoretical results, the HRR field in this case, without adequate experimental and numerical verifications.

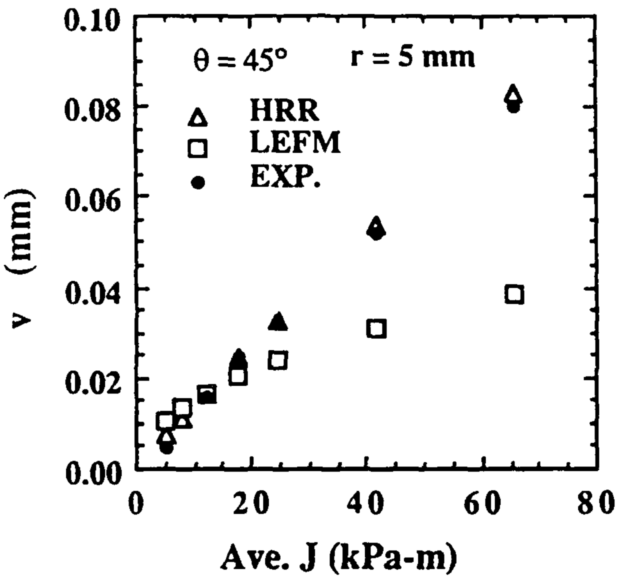

Fig. 6(a) v-Displacement in 5052-H32 Cruciform Specimen.

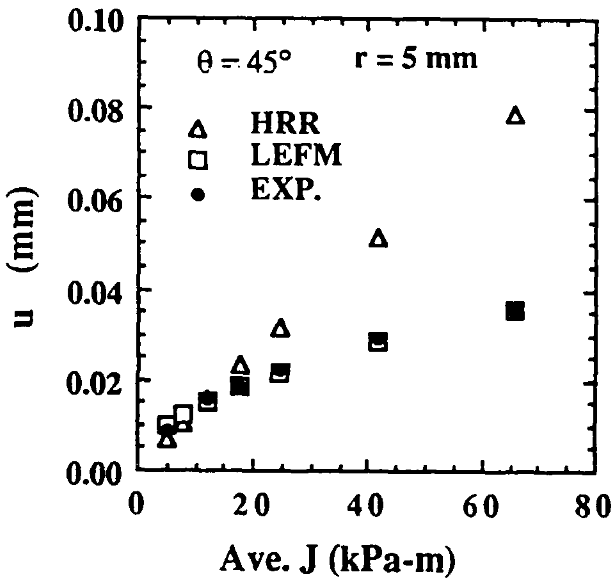

Fig. 6(b) u-Displacement in 5052-H32 Cruciform Specimen.

Our findings are particularly sensitive to the accuate determination of the crack tip location which is obscured by the caustics surrounding the crack tip. In this study, the center of the caustics was found to be a reasonable approximation of the crack tip as shown by the overexposed photograph of the crack which is superimposed onto the v-field moire patterns of Figure 7. A sensitivity analysis of the v- and u-fields also showed that a 1 mm horizontal shift in the crack tip location would shift the v-field off from the predicted HRR v-field. While the good agreement between the measured and computed v-field in our study does not validate the experimental analysis, had the crack tip been shifted horizontally from the center of the caustics, then neither the measured v- nor u-field would coincide with the respective HRR fields.

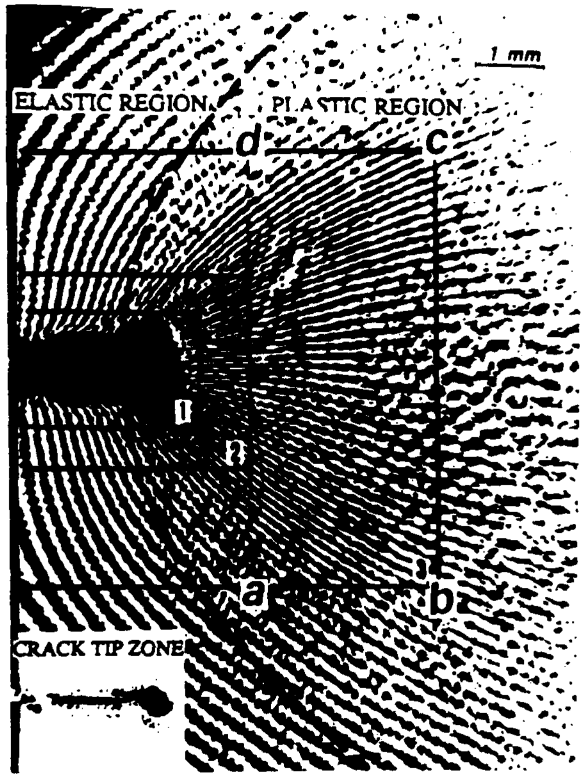

Figure 7. V-Displacement in 5052-H32 Al. Small SEN Specimen.

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HRR Field, J-integral, Biaxial Loading, LEFM, Moire Interferometry, Elastic-Plastic Fracture Mechanics, J-Resistance Curve and Stable Crack Growth.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The displacement fields surrounding stably growing cracks in 7075-T6, 2024-0, 2024-T3, 5052-H32 and 2091 aluminum alloy, standard and cruciform, single-edge notched (SEN) specimens were determined by moire interferometry. An approximate and exact J-integral values were determined and found to be within 5% of each other and were both path independent. The associated HRR crack tip displacements in all specimens were in agreement with the measured displacements vertical to the crack but consistently differed in magnitude and order of singularity with the measured displacements parallel to the crack.