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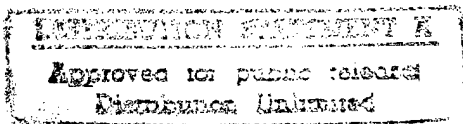
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FINAL TECHNICAL REPORT

MOIRE FOR DYNAMIC FRACTURE

by

Albert S. Kobayashi



August 1997

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Department of Mechanical Engineering

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1. Objective

The objective of this research program is to investigate experimentally the transient strain and stress distributions in the vicinity of a running crack in engineering materials.

2. Technical Approach and Accomplishments

ONR Research Grant No. N00014-96-1-1218 commenced on August 1, 1996 and terminated on June 30, 1997. For coherency in reporting, some accomplishments made on the previous ONR Research Grant No. N00014-89-J-1276 are included in the following.

Hybrid experimental-numerical and experimental analyses were used to explore possible dynamic ductile fracture parameters associated with rapid crack propagation in 7075-T6 and 2024-T3 aluminum alloy, single edge notched (SEN) specimens of 1.6 mm thickness. Dynamic Moiré interferometry was used to record the crack tip displacement field, which was used either to drive a dynamic elasto-plastic finite element (FE) model of the fracturing SEN specimens or by itself, to determine the crack-tip J-integral, the T^*_ϵ -integral and the crack tip opening angle (CTOA).

Several experimental obstacles had to be overcome to obtain these results. Initially Moiré interferometry was used to determine only the transient displacement field perpendicular to the running crack, i.e. the v-field in fatigue-precracked 7075-T6 and 2024-T3 SEN specimens (1st series experiment). The missing displacement field parallel to the crack, i.e. the u-field, was computed through the use of a hybrid experimental-numerical analysis where the measured transient displacement field together with the crack propagation history drove a dynamic, elasto-plastic FE model of the SEN specimen. The u- and v-displacement fields obtained through this FE analysis were then used to extract fracture parameters, such as the J and the T^*_ϵ -integrals and the CTOA, of the propagating ductile crack by a procedure developed by Okada and Atluri¹.

Results and experience gained from the above first series of experiment led to the development of a purely experimental procedure involving only the Moiré interferometry. In this procedure, the displacements perpendicular and parallel to the running crack, v and

¹ Okada, H. and Atluri, S. N. (1997). Further Study on the Near Tip Integral Parameter T^*_ϵ in Stable Crack Propagation in Thin Ductile Plate. *Proc. of Aerospace Div.*, ASME, AD-Vol. 52, Eds. J.C.L. Chang et al, 251-260.

u, respectively, were recorded separately in a multitude of machine-notched SEN specimens (2nd series experiment) of identical geometry. The results of these tests were then assembled as a combined transient u and v displacement records which were used to compute directly the T^*_ϵ by the same procedure (Okada and Atluri).

The results of the first series of experiments showed that the near-field J vanished but the near-field T^*_ϵ remained constant with crack propagation as shown by Figure 1. The

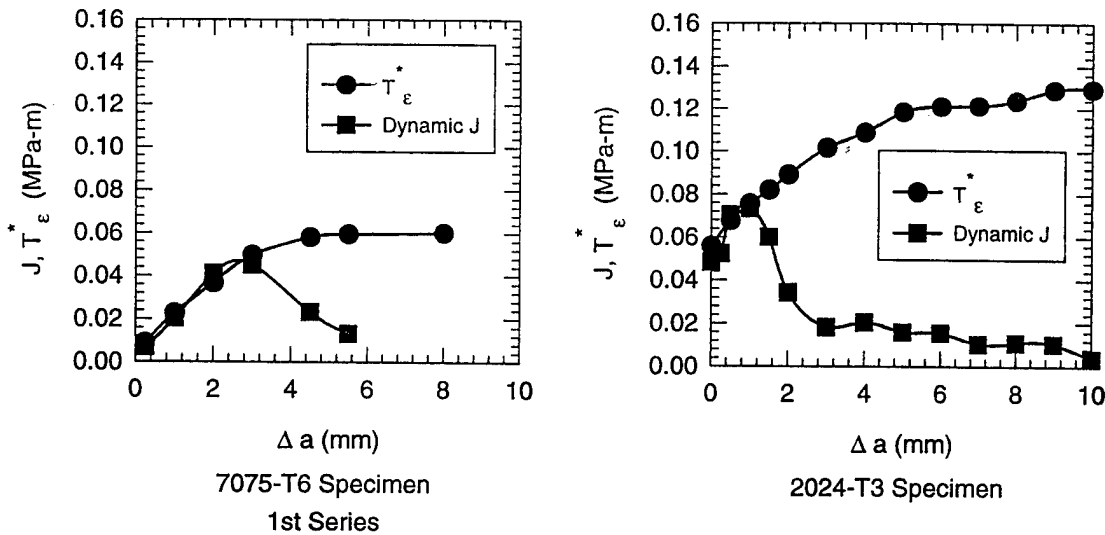


Figure 1 J and T^*_ϵ variations in aluminum SEN specimens
 $\epsilon = 2 \text{ m}$

CTOA associated with a low crack velocity, also remained constant during crack propagation but fluctuated at the higher crack velocity as shown in Figure 2. Figure 3 shows the T^*_ϵ versus crack velocity relations of the 7075-T6 and 2024-T3 SEN specimens. T^*_ϵ increased with increased crack velocity and leveled off at a terminal velocity of about 300 m/s in 7075-T6 SEN specimens. In contrast, the crack did not reach its terminal velocity in the fatigue precracked 2024-T3 SEN specimens and arrested at a T^*_ϵ higher than its initiation value.

The dynamic stress intensity factor, K_{ID} , with respect to crack velocity of 7075-T6, like other somewhat brittle material, was expected to exhibit the characteristic gamma-shaped curve. To test this postulate, the crack tip opening displacement (COD) at a crack

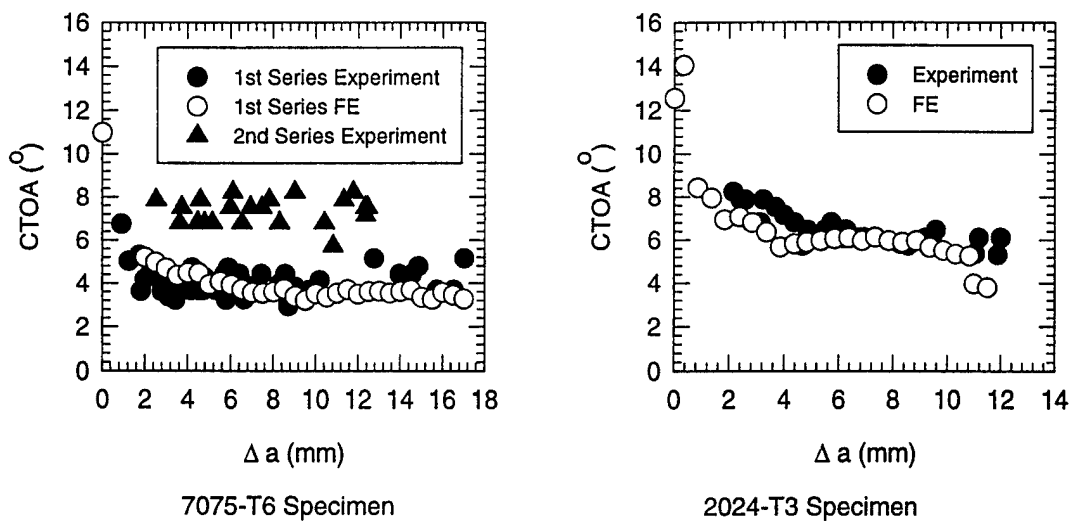


Figure 2 CTOA variations in aluminum SEN specimens.

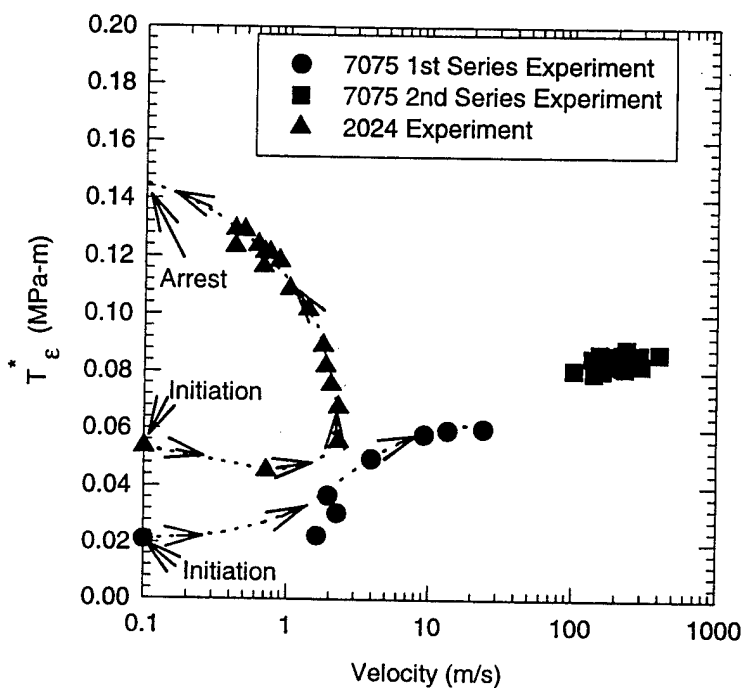


Figure 3 T^*_ϵ variation with crack velocity

tip distance, $r = 1$ mm, was used to compute K_{ID} , and hence the strain energy release rate, G_D , based on LEFM of both the fatigue-precracked (first series) and machine-notched

(second series) 7075-T6 SEN specimens. The same procedure was used to compute G_{ID} of the blunt-notched 7075-T6 SEN specimens of 1967². The characteristic gamma shaped G_{ID} versus crack velocity relation is apparent in Figure 4.

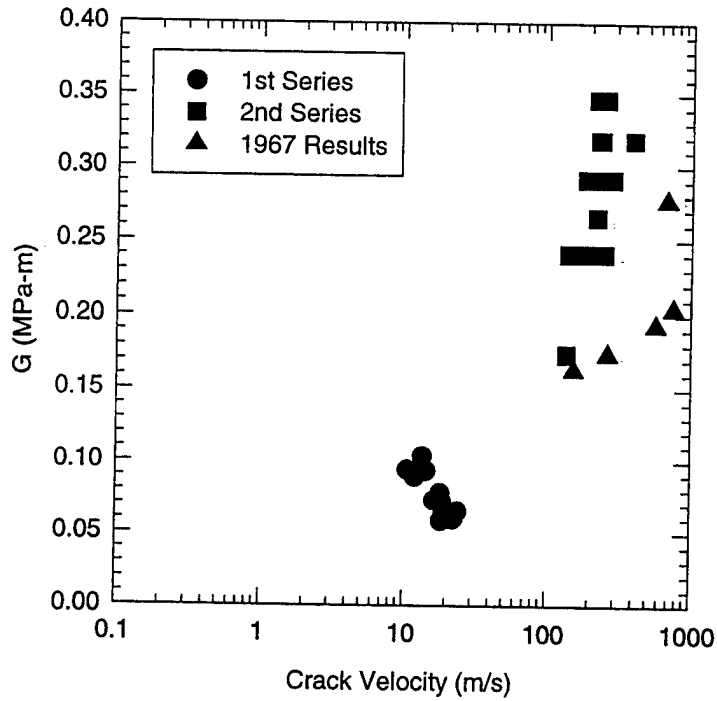


Figure 4 G_{ID} variation with crack velocity

The results of this preliminary study suggests that the T_{ϵ}^* criteria proposed for stable crack growth could be a suitable parameter for rapid crack propagation in these thin aluminum specimens. At the limiting crack velocity, T_{ϵ}^* reached a physically more reasonable saturation value in comparison to the widely varying K_{ID} .

3. Navy Relevance

Many naval structures are fabricated with ductile materials, such as medium strength steel and aluminum. While the utmost concern is to avoid catastrophic failure in the many

² Kobayashi, A. S. and Engstrom, W. L. (1967), "Transient analysis in fracturing aluminum plates," *Proc. 1967 JSME Semi-International Symposium*, 172-181.

aging naval structures with pre-existing fatigue cracks, a secondary concern is to predict the extent of maximum crack extension or to design crack arresters in the event of a rapid crack propagation due to the unavoidable hostile environment. The popular J-integral criterion, currently in use by the USN, has been shown by the PI and others to lack physical significance. On the other hand, the T^*_e shows promise as a suitable dynamic ductile crack propagation and a dynamic arrest criteria for use in naval structures.

4. Acknowledgement

This research program in dynamic fracture mechanics terminated on June 30, 1997 after 33 years of continuous ONR support which provided the PI with unparalleled opportunities in his professional career. The PI gratefully acknowledges the ONR support which made him of what he is today.

5. List of Publications/Reports/Presentations

5.1. Papers Published in Refereed Journals:

"Dynamic Ductile Fracture of Aluminum SEN Specimens - An Experimental-Numerical Analysis," J. Lee, M. K. Kokaly and A. S. Kobayashi, submitted to the International Journal of Fracture.

"Hybrid Method in Elastic and Elasto-plastic Fracture Mechanics," to be published in Hybrid Methods in Experimental Mechanics, ed. M. Takashi, Optics and Laser Engineering.

5.2. Non-Refereed Publications and Published Technical Reports:

"Dynamic Ductile Fracture of Aluminum SEN Specimens--An Experimental-Numerical Analysis," J. Lee, M.T. Kokaly and A.S. Kobayashi, Applied Mechanics in the Americas, Vol. 4, eds. L.A. Goody, M. Rysz and L.E. Suarez, pp 77-80, The University of Iowa, 1996.

"Dynamic Ductile Fracture of Aluminum SEN Specimens--An Experimental-Numerical Analysis," J. Lee, M.T. Kokaly and A.S. Kobayashi, Advances in Fracture Research, ICF9, B.L. Karihaloo, Y. W. Mai, M.I. Ripley and R.O. Ritchie, Pergamon Press, 1997, pp. 2965-2972. (Reviewed)

"Static/Dynamic T^*_ϵ of Aluminum Fracture Specimens," S.N. Atluri and A.S. Kobayashi, *Advances in Computational Engineering Sciences*, eds. S.N. Atluri and G. Yagawa, Tech. Science Press, 1997, pp. 158-164..

"U.S. Engineering Education of the 21st Century," Int'l. Conf. on Materials and Mechanics '97, ed. H. Nakamura, JSME, 1997, pp.623-266.

5.3a. Invited Presentations:

" T^*_ϵ Integral as a Crack Growth Criterion," Washington State University, Pullman, WA, October 9, 1996,

" T^*_ϵ Integral as a Crack Growth Criterion," Japan Society for Naval Architects, Tokyo, October 22; Japan Society of Materials Science, Nagoya, October 30 and Tokyo Institute of Technology, Tokyo, October 23, plus two industrial laboratories, October 21 and 25, 1996.

"Axial Crack Propagation and Arrest in Pressurized Fuselage," Yokohama National University, Yokohama, October 23 and Chubu University, Kasugai, October 31, plus two industrial laboratories, October 29 and November 1, 1996.

"Elastic-plastic Fracture Mechanics A Personal Prospective," Aoyama Gakuin University, October 24, 1996.

" T^*_ϵ as a crack Growth Criteria," Keynote Lecture, ICES'97, San Jose, Costa Rica, May 7, 1997.

5.3b. Contributed Presentations:

First two listed in Section 5.2.

5.4. Books (and Sections thereof):

None

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13. ABSTRACT (Maximum 200 words) Moiré interferometry was used to record the displacement field surrounding a rapidly propagating crack in thin aluminum fracture specimens. The J- and T_e^* -integral values were computed directly, for the first time, from the displacement data. J, T_e^* and CTOA values were also obtained by dynamic, elastic-plastic finite element simulations of the fracture tests. While the near-field J precipitously dropped to zero, the near-field T_e^* and CTOA reached a steady state value with crack extension and were found to be a suitable fracture parameter for characterizing rapid crack growth and arrest.			
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