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J-INTEGRAL MEASUREMENT USING NOIRE INTERFEROMETRY(U)
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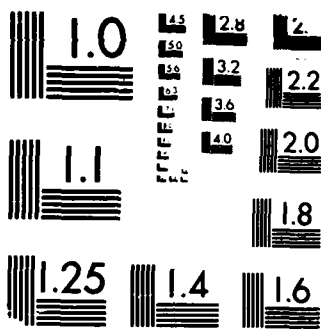
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J-INTEGRAL MEASUREMENT USING MOIRÉ INTERFEROMETRY

M. S. Dadkhah, A. S. Kobayashi, F. X. Wang and D. L. Graesser

April 1988

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J-INTEGRAL MEASUREMENT USING MOIRÉ INTERFEROMETRY

* M. S. Dadkhah, ** A. S. Kobayashi, *** F. X. Wang and **** D. L. Graesser

ABSTRACT

An improved moiré interferometry, which records both the vertical and horizontal displacements simultaneously, was used to determine the J-integral within the confine of a constitutive relation. J-values, which are associated with stable crack growth in biaxially loaded 2024-T3 aluminum, single edge notched specimens, were found to be path independent and increased with crack extension.

KEY WORDS

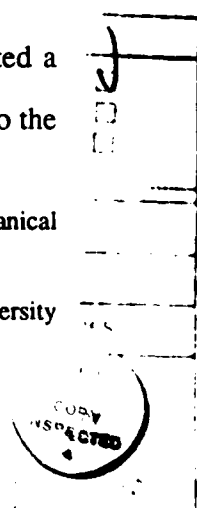
include
J-integral, Biaxial Loading Machine, Moiré Interferometry, Elastic-plastic Fracture Mechanics, Simultaneous displacement fields, Automated Data Reduction Displacement Fields, J-resistance curve and Stable crack growth.

INTRODUCTION

In two previous papers [1,2], one of the author and his colleagues presented a procedure for estimating the J-integral values using only the displacements vertical to the

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crack in a single edge notched specimen. This restriction was imposed by the requirement for rapid recordings of a transient displacement field, which was obtained by moiré interferometry, associated with stable crack growth and rapid tearing of a ductile material. Extensive error analysis showed that this estimation procedure provided reasonably accurate J-values in single edge notched specimens.

The above restriction has been removed in an improved moiré interferometry setup where both the vertical and horizontal displacements are recorded simultaneously in a single frame [3]. The improved procedure is conducive to high speed photography and a procedure was developed for determining the J-integral value exactly within the confine of the constitutive relation. This procedure was used to determine the J-values associated with stable crack growth in biaxially loaded, 2024-T3 aluminum, single edge notched specimens, 0.8 mm thick, as shown in Figure 1. Biaxiality ratios of $B = 0.0, 2.0$ were applied through a special biaxial testing machine [4] and stable crack growth in excess of 5 mm were obtained prior to rapid tearing. The J-values were evaluated along the three contours encompassing the crack.

EXPERIMENTAL PROCEDURE

An improved four-beam moiré interferometry system was used to measure two orthogonal in-plane displacement fields simultaneously [3]. This experimental setup is nearly identical to that described by Post [5], except that a polarizing beam-splitter and a prism are placed between the emerging moiré patterns and the camera lens, as shown in Figure 2. The beam-splitter separates the u and v displacement fringe patterns and the prism projects them onto the same frame of a photographic system.

Automated Data Reduction Displacement Fields

The data reduction scheme used in this study is an automated data reduction version of the recorded u and v displacement fields [6,7,8]. The technique was automated through the use of modern digitizing and computer equipment. The two primary pieces of equipment required are an AST Turboscan Digitizer and a Macintosh II computer. The digitized moiré patterns, which are created using the AST Turboscan system, are stored in a bit map file, which in essence contains pixel information for every point on the image. The original $38.1 \times 38.1 \text{ mm}^2$ ($1.5 \times 1.5 \text{ in}^2$) grating area is represented by 7,200,000 pixel points in the digitized image. The program STRAIN computes displacement derivatives in either the horizontal or vertical directions. Normal strain, ϵ_x , is determined from the u -displacement image, i.e. $\epsilon_x = du/dx$, while ϵ_y is determined from the v -displacement image, i.e. $\epsilon_y = dv/dy$. The shear strain ϵ_{xy} is found by taking the derivatives du/dy and dv/dx and summing them in the fashion: $\epsilon_{xy} = 1/2(du/dy + dv/dx)$.

The evaluation of the J-Integral is essentially a numerical integration along a loop encompassing the crack where the three strain components must be evaluated at identical points along the chosen path. Program STRAIN calculates strains at fringe center locations, which may or may not be exactly on the chosen path. Thus an interpolation program (INTRP), which calculates the strains at every pixel point along the contour in the computer image, was developed. The positions of the u and v displacement fields may not be identical in the two photographs, therefore, INTRP requires that offset values be entered relating the relative position of the "origins" in the two fields, i.e., du/dx and du/dy are calculated for the given path, while dv/dx and dv/dy are calculated for a path on the v displacement field which corresponds to the path taken on the u displacement field. This process ensures that the numeric integration is using three components of strain from the same location.

J Integral Evaluation

The evaluation of the J-Integral requires the strain components, the stress components and the strain energy density [9,10]. The three components of stress are calculated using J_2 -deformation theory of plasticity for multi-axial states with a power hardening stress-strain relation. A Newton-Raphson routine was used to solve the three coupled nonlinear constitutive equations. The strain energy density is calculated using the stress and strain components calculated above.

The J-measurement, which was derived for rectangular contours surrounding the crack tip, is divided into line integrals along the vertical and horizontal segments shown in Figure 1. The integral value of J along the vertical segments is:

$$J_V = \int_{V_1} \left[W - \left(\sigma_{xx} \frac{\partial u}{\partial x} + \tau_{xy} \frac{\partial v}{\partial x} \right) \right] dy - \int_{V_2} \left[W - \left(\sigma_{xx} \frac{\partial u}{\partial x} + \tau_{xy} \frac{\partial v}{\partial x} \right) \right] dy \quad (1)$$

and along the horizontal segments the value of J is:

$$J_H = - \int_{H_1} \left(\sigma_{yy} \frac{\partial v}{\partial x} + \tau_{xy} \frac{\partial u}{\partial x} \right) dx + \int_{H_2} \left(\sigma_{yy} \frac{\partial v}{\partial x} + \tau_{xy} \frac{\partial u}{\partial x} \right) dx \quad (2)$$

$$J = J_V + J_H \quad (3)$$

Accuracy of this J-evaluation procedure was assessed by evaluating equations (1) and (2) along a 4.2 cm contour, which did not enclosed the crack tip, using the moiré fringe data of

specimen MD031687-838. The resultant $J = 49.01$ (pa-m), which theoretically should vanish, was 0.4 % of the minimum recorded J-value in this paper.

RESULTS

Figure 3 shows typical moiré fringe patterns corresponding to the u and v displacement fields in a biaxially loaded aluminum specimen. Figure 4 shows the two normal strains, ϵ_x and ϵ_y , for the displacement fields shown in Figure 3. Due to large plastic deformation axial strain regions are no longer of the familiar butterfly shape. Figure 5 shows the stress-strain relation of the 2024-T3 aluminum specimen with the coefficients for the power hardening relation.

Figures 6 and 7 show the J_R -curves for uniaxially ($B = 0$) and biaxially loaded ($B = 2$) 2024-T3 aluminum specimens. 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 infer critical $J_{Ic} = 5500$ and 6300 Pa-m for uniaxially and biaxially loaded specimens, respectively.

Figures 8 and 9 show the log-log plots of the v -displacement fields toward the last crack extension increment. For a HRR field [10] to hold, the slope of these curves should be $\frac{1}{n+1} = 0.1$. The extent of the HRR fields can be estimated in Figures 8 and 9 by bounding the slopes of the v displacements to ± 10 % of its theoretical value. The extent of HRR field in this experiment was about 8.8 mm ahead of crack tip.

CONCLUSIONS

- 1) J is path independent for crack extensions of 4 mm for $B = 0$ and $B = 2$.
- 2) J_R curves are identical within the scatter of data for both $B = 0$ and $B = 2$.
- 3) HRR field extended 8.8 mm from the crack tip.

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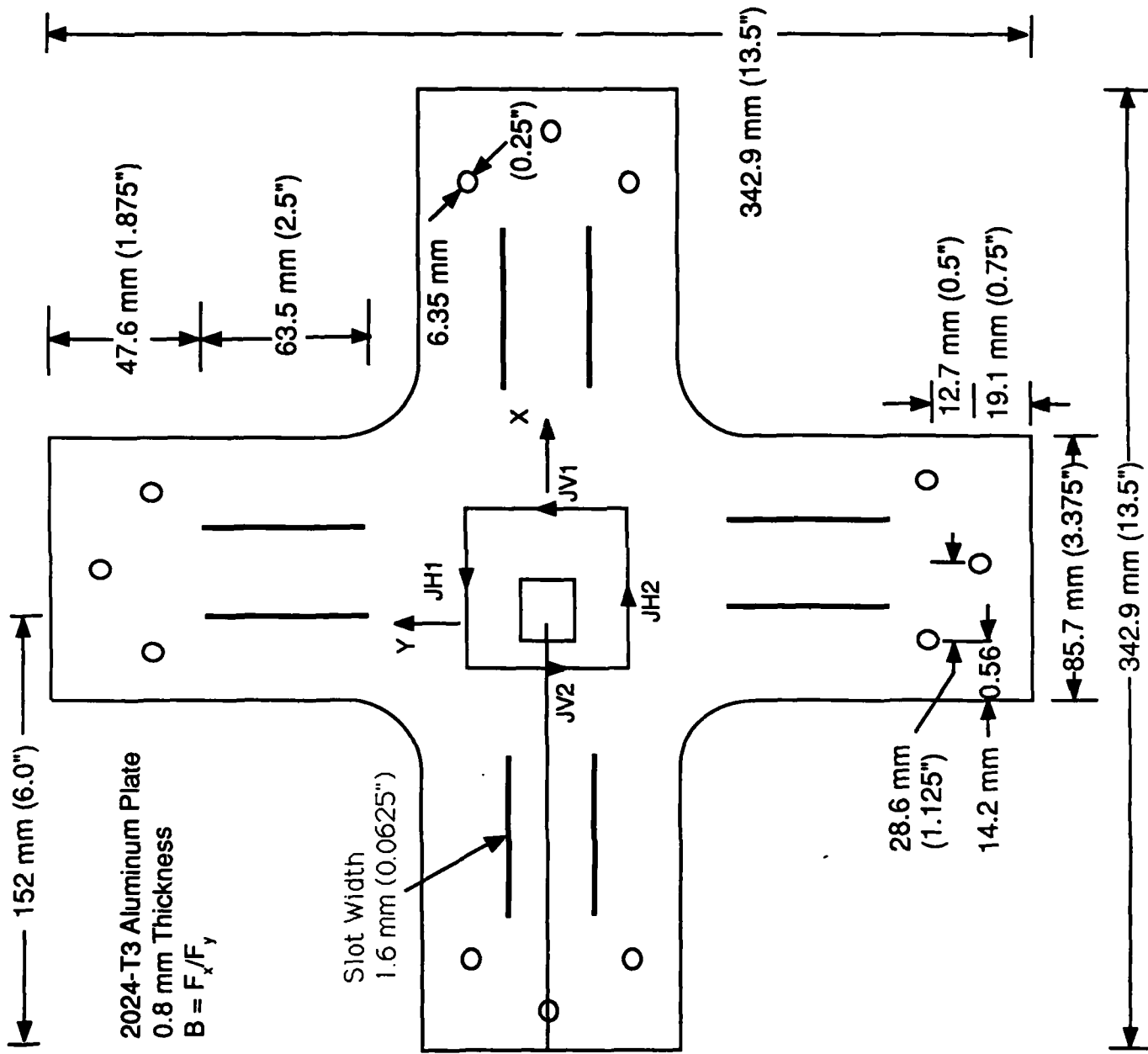


Figure 1 Specimen Configuration and J-integration Paths

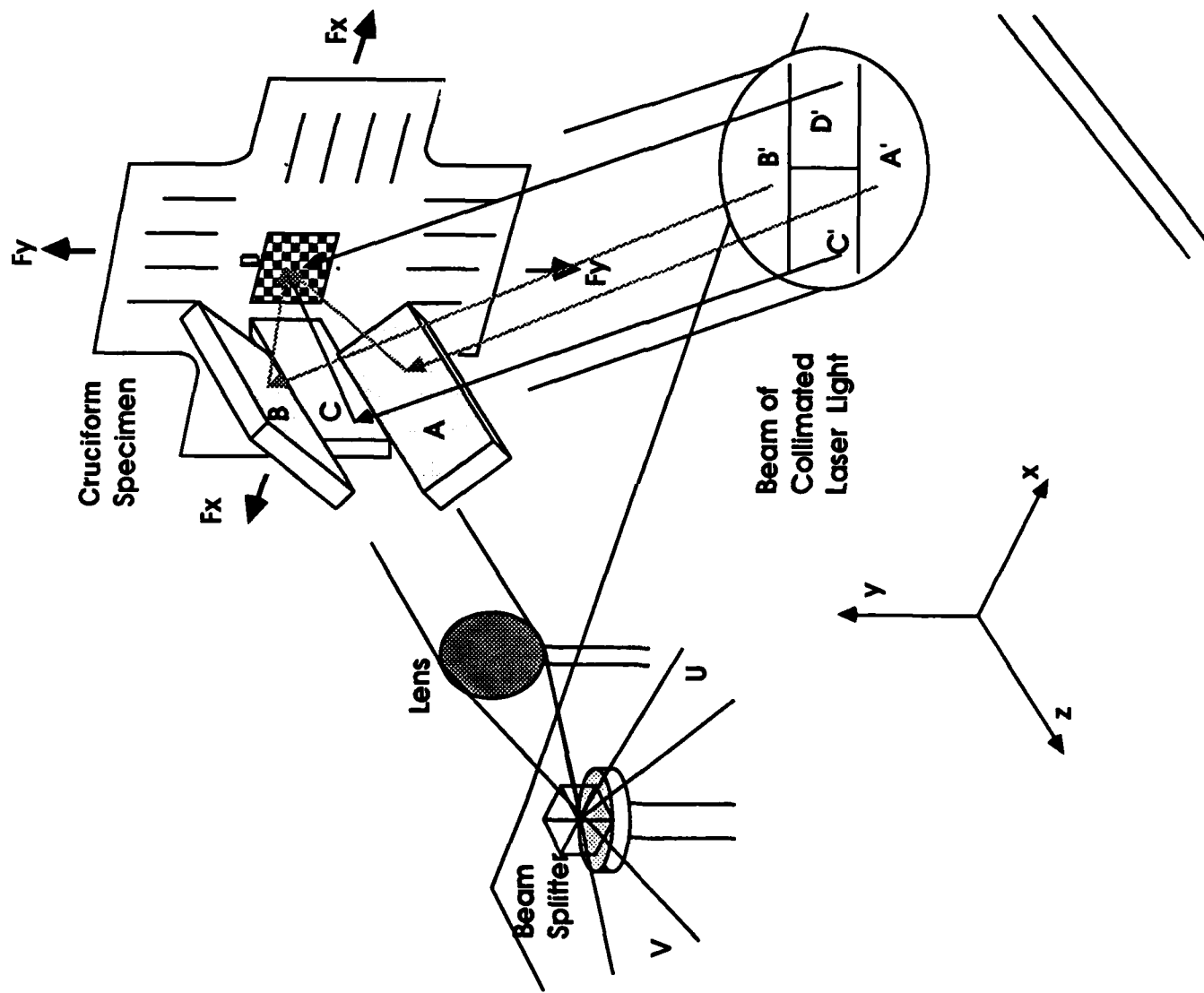
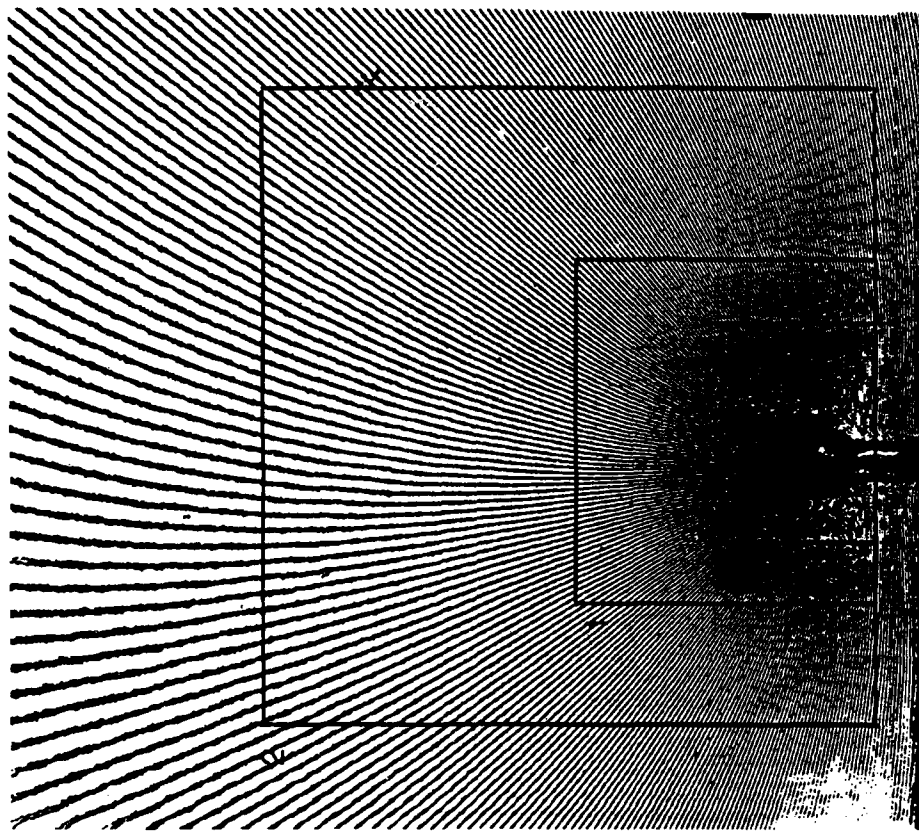
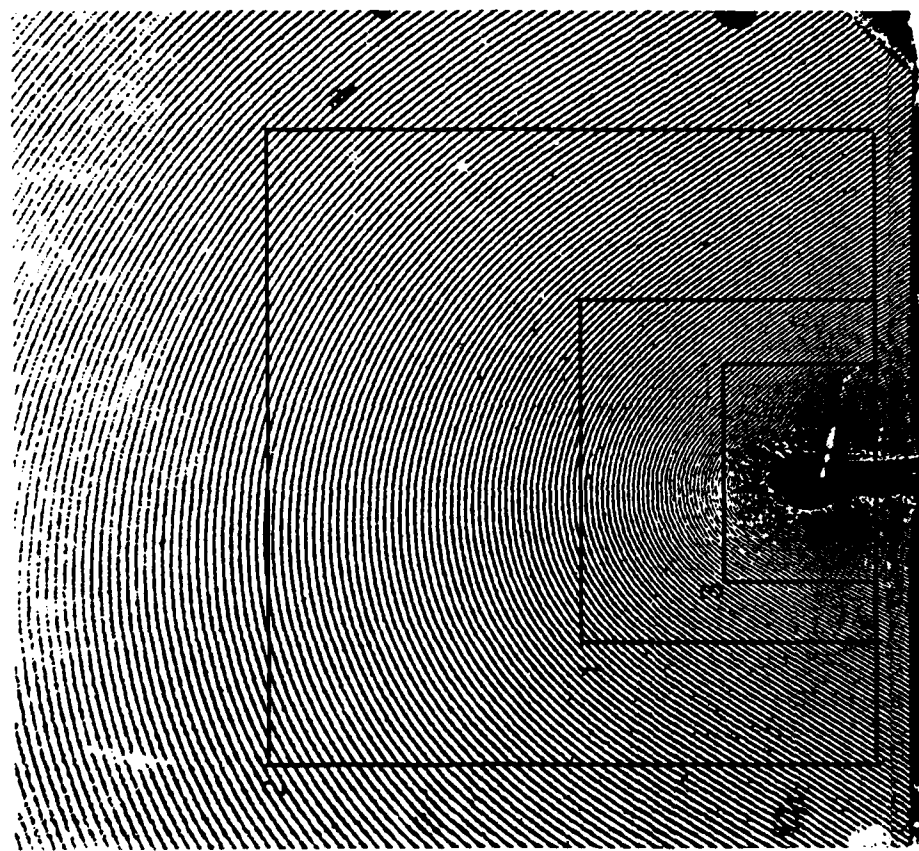


Figure 2 A 4-beam Optical Arrangement to Produce the u Pattern with Beams C' and D', The v Pattern with Beams A' and B'.



v displacement field

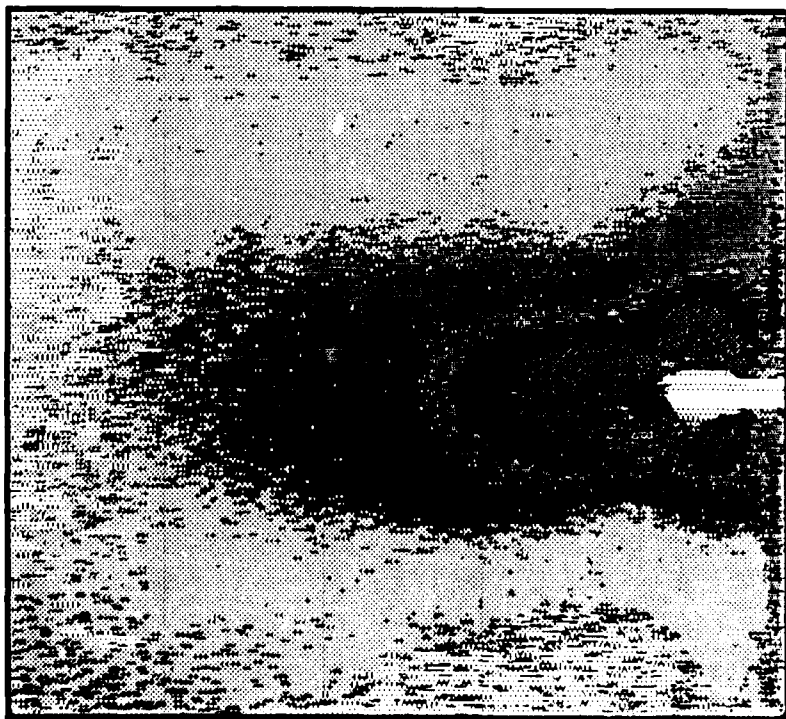


u displacement field

— 5 mm —

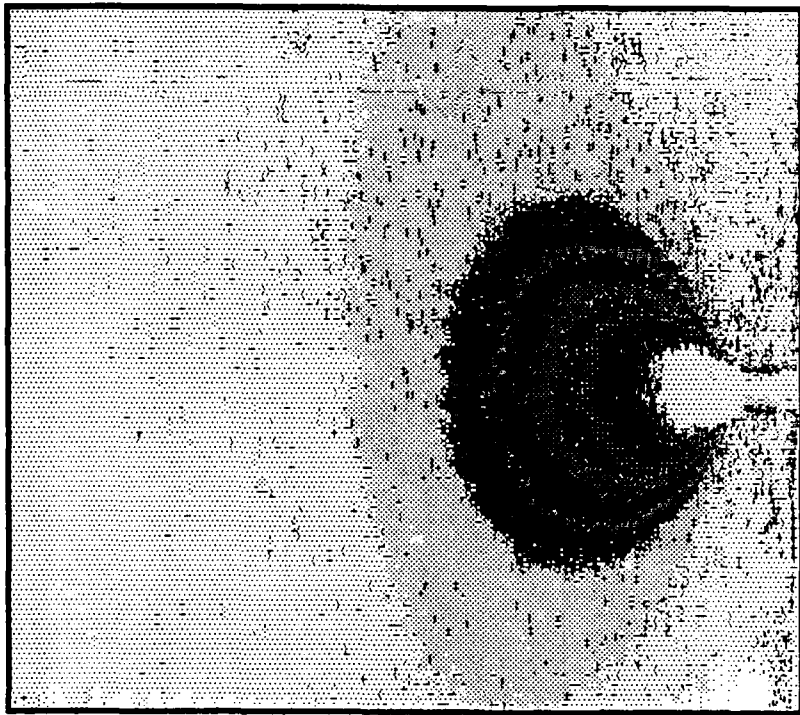
Figure 3 u- and v-displacement Fields for Test MD101987-8.
 (J-integration Paths Shown in Each Figure)
 $F_x=17$ KN, $F_y=8.8$ KN, $B=2$.

1-5 mm



- strain = 1521 to 2615 ($\mu\text{m}/\text{m}$)
- strain = 2615 to 3709 ($\mu\text{m}/\text{m}$)
- strain = 3709 to 4803 ($\mu\text{m}/\text{m}$)
- strain = 4803 to 5897 ($\mu\text{m}/\text{m}$)
- strain = 5897 to 6991 ($\mu\text{m}/\text{m}$)
- strain = 6991 to 8085 ($\mu\text{m}/\text{m}$)
- strain = 8085 to 9178 ($\mu\text{m}/\text{m}$)
- strain = 9178 to 35130 ($\mu\text{m}/\text{m}$)

ϵ_x strain field



- strain = 1636 to 3012 ($\mu\text{m}/\text{m}$)
- strain = 3012 to 4388 ($\mu\text{m}/\text{m}$)
- strain = 4388 to 5764 ($\mu\text{m}/\text{m}$)
- strain = 5764 to 7140 ($\mu\text{m}/\text{m}$)
- strain = 7140 to 8516 ($\mu\text{m}/\text{m}$)
- strain = 8516 to 9892 ($\mu\text{m}/\text{m}$)
- strain = 9892 to 11270 ($\mu\text{m}/\text{m}$)
- strain = 11270 to 44290 ($\mu\text{m}/\text{m}$)

ϵ_y strain field

Figure 4 Normal Strain Fields in Biaxially Loaded 2024-T3 Aluminum Specimen.
 $F_x=17$ KN, $F_y=8.8$ KN and B=2 for test MD101987-8.

Stress vs. Strain

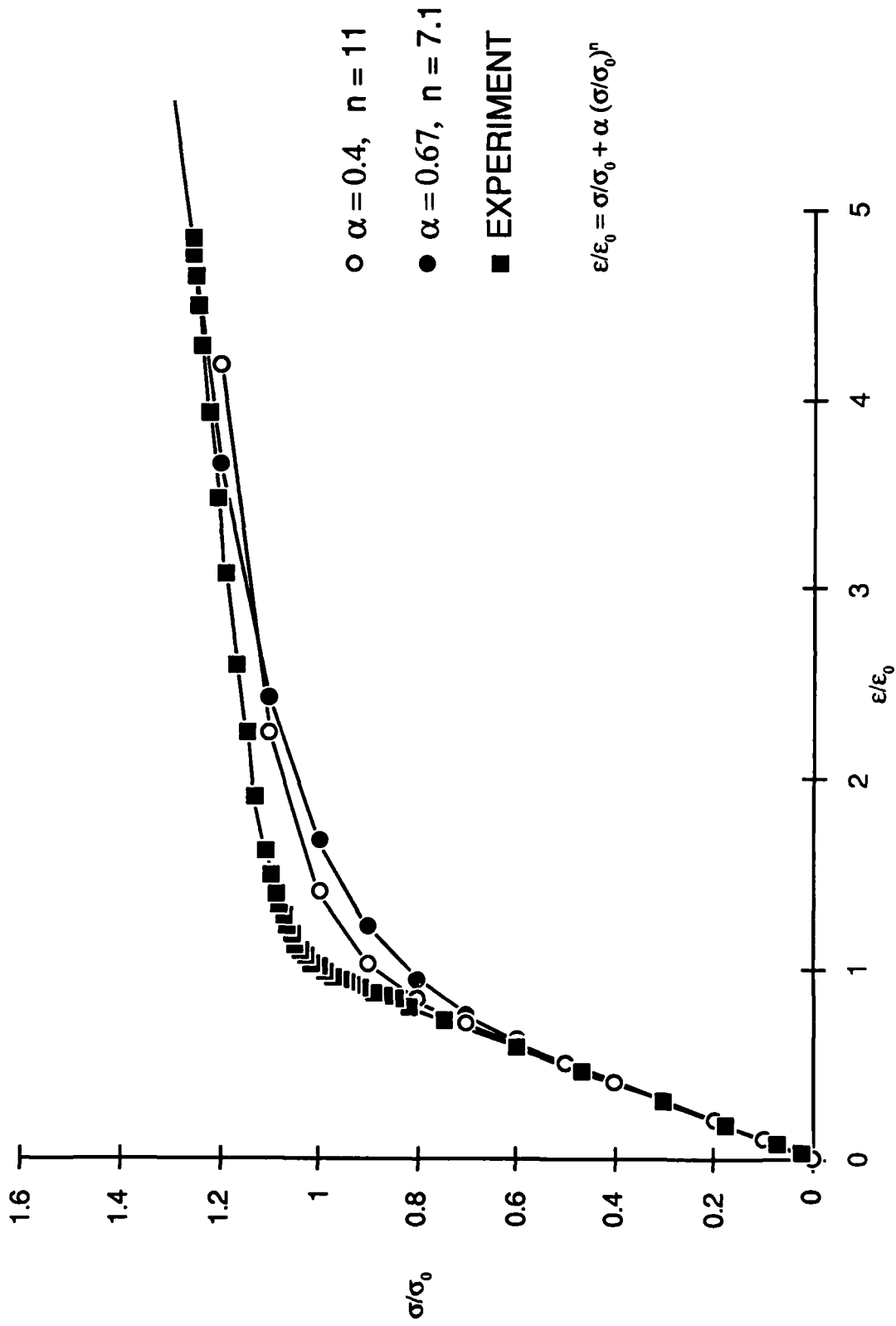


Figure 5 Stress-Strain Relation of 2024-T3 Aluminum 0.8 mm Thickness.

J_R CURVE
B=0

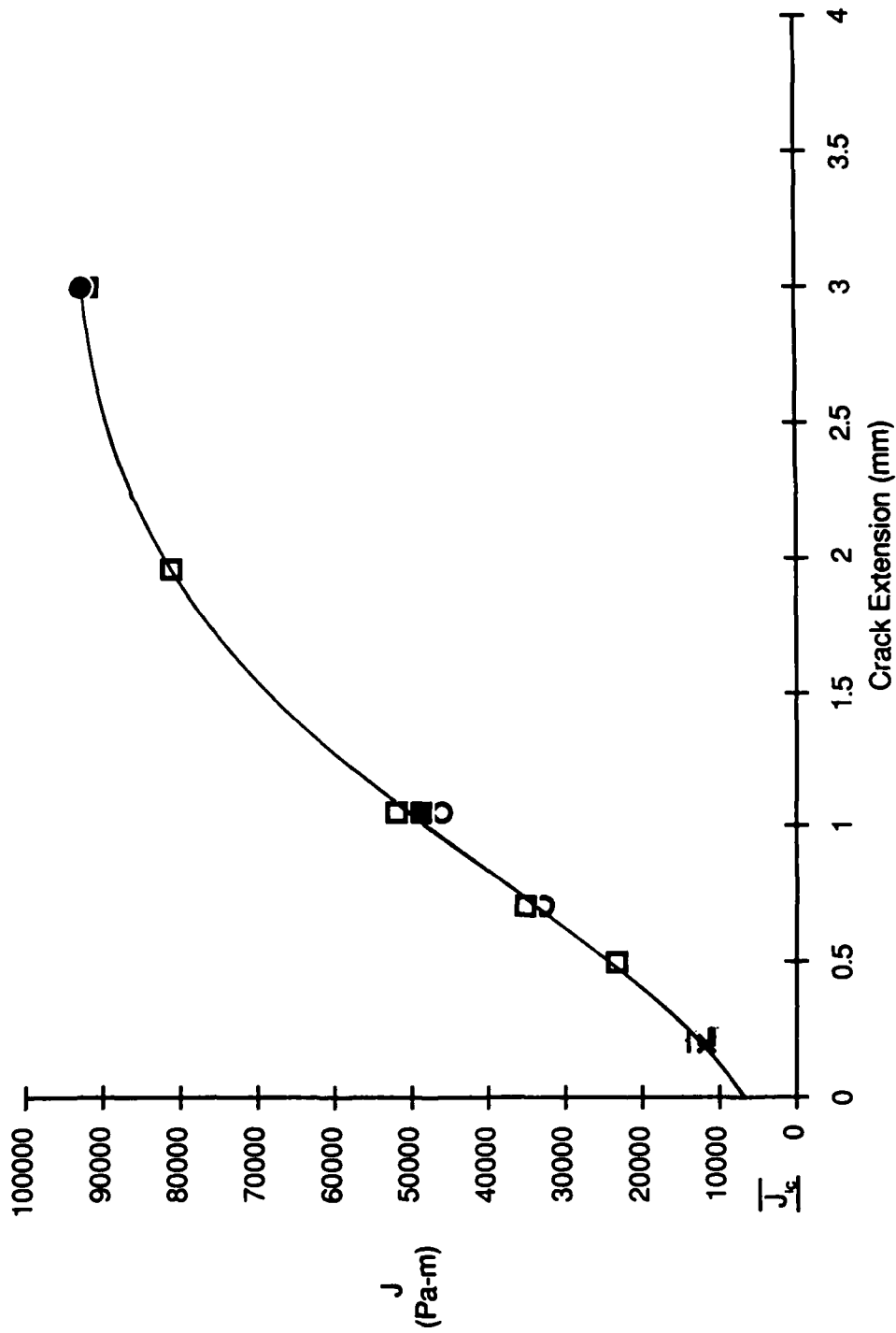


Figure 6 J Values Versus Crack Extension, 2024-T3 Aluminum Specimen MD031687, B=0.

J_R CURVE
B=2

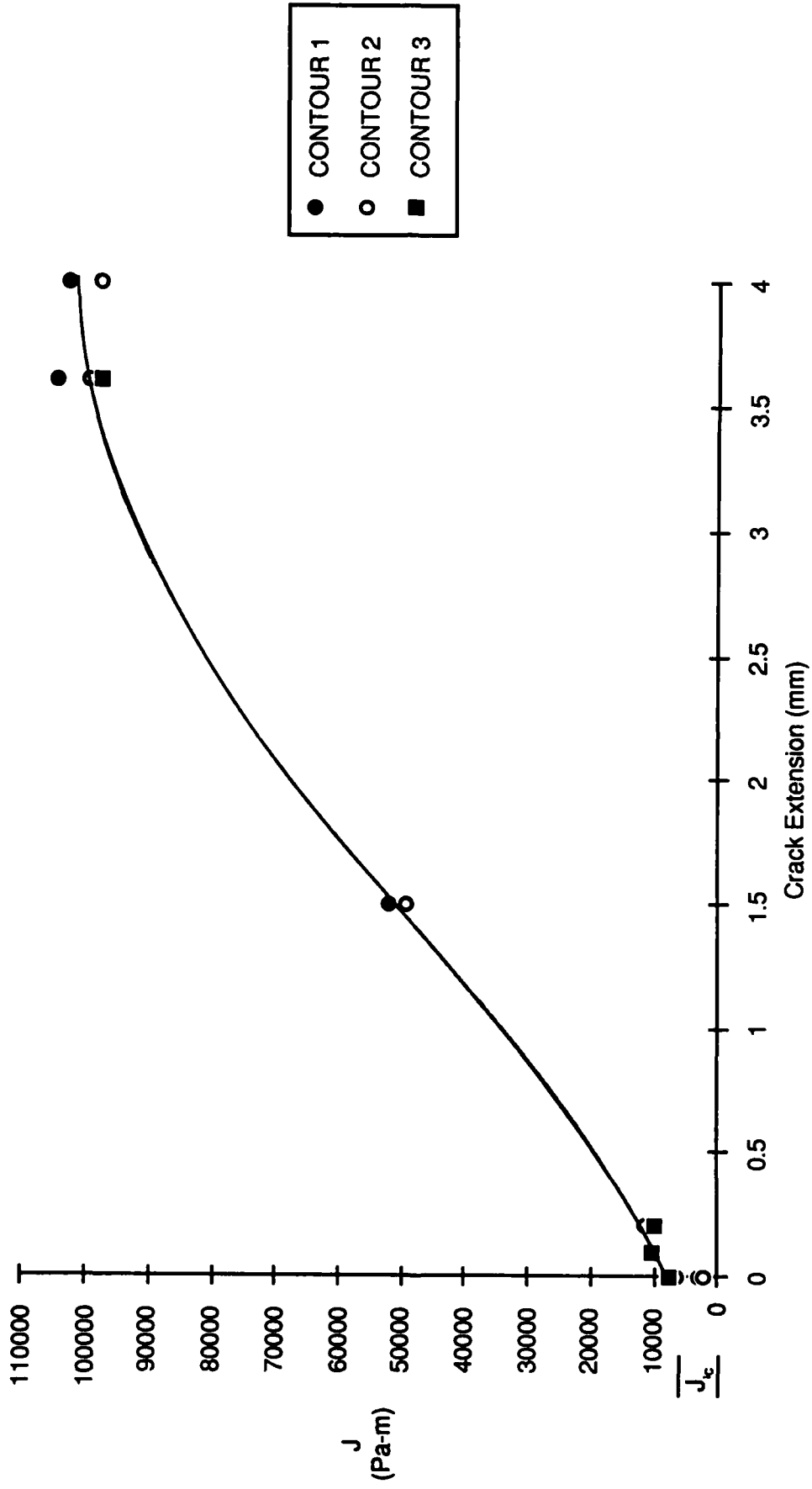


Figure 7 J Values Versus Crack Extension, 2024-T3 Aluminum Specimen MD101987, B=2.

log r - log v for MD031687-1554 B=0

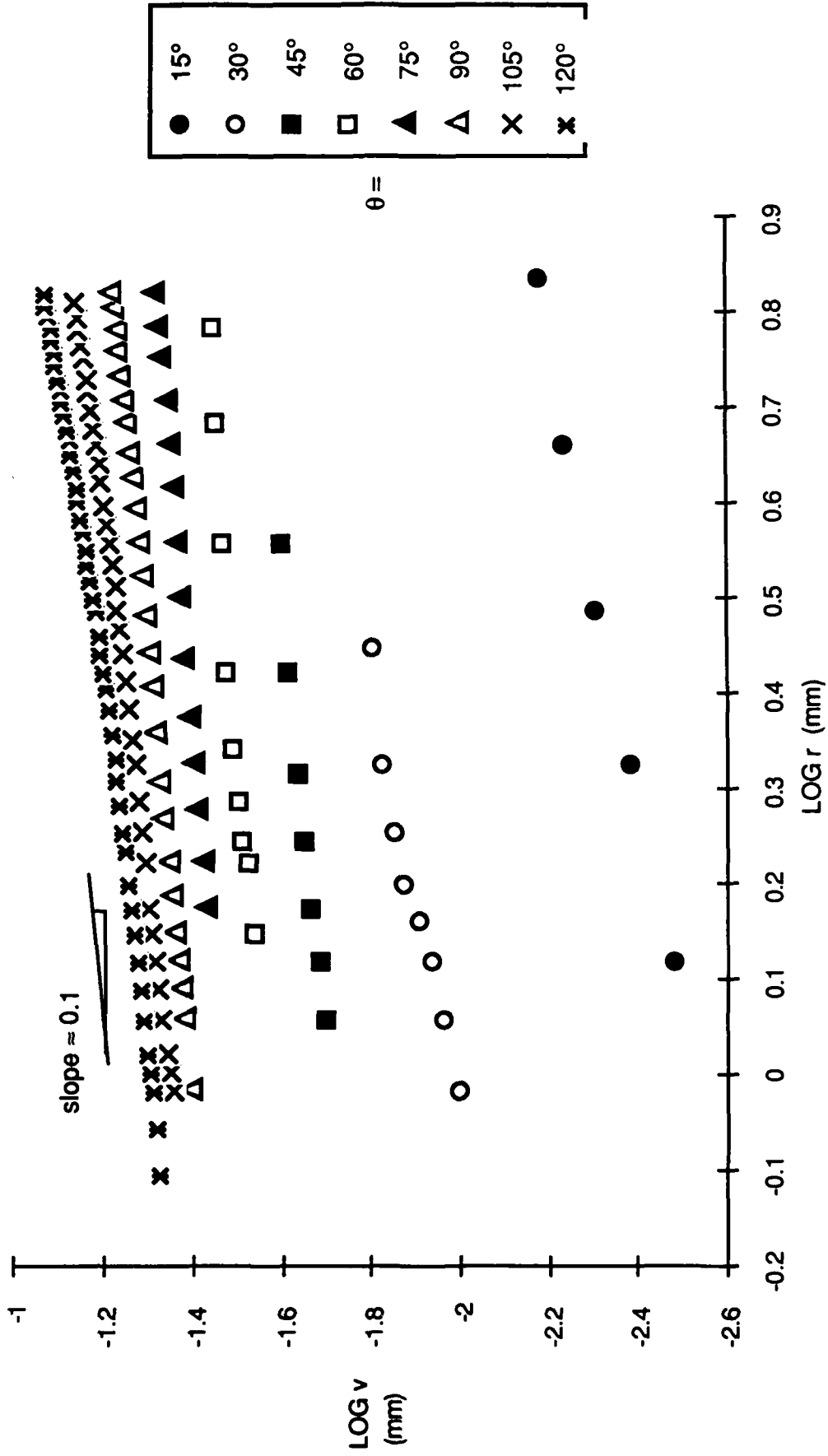


Figure 8 Log v Versus Log r Plots of 2024-T3 Aluminum SEN Specimen MD031687-1554, B=0.

log r - log v for MD101987-8 B=2

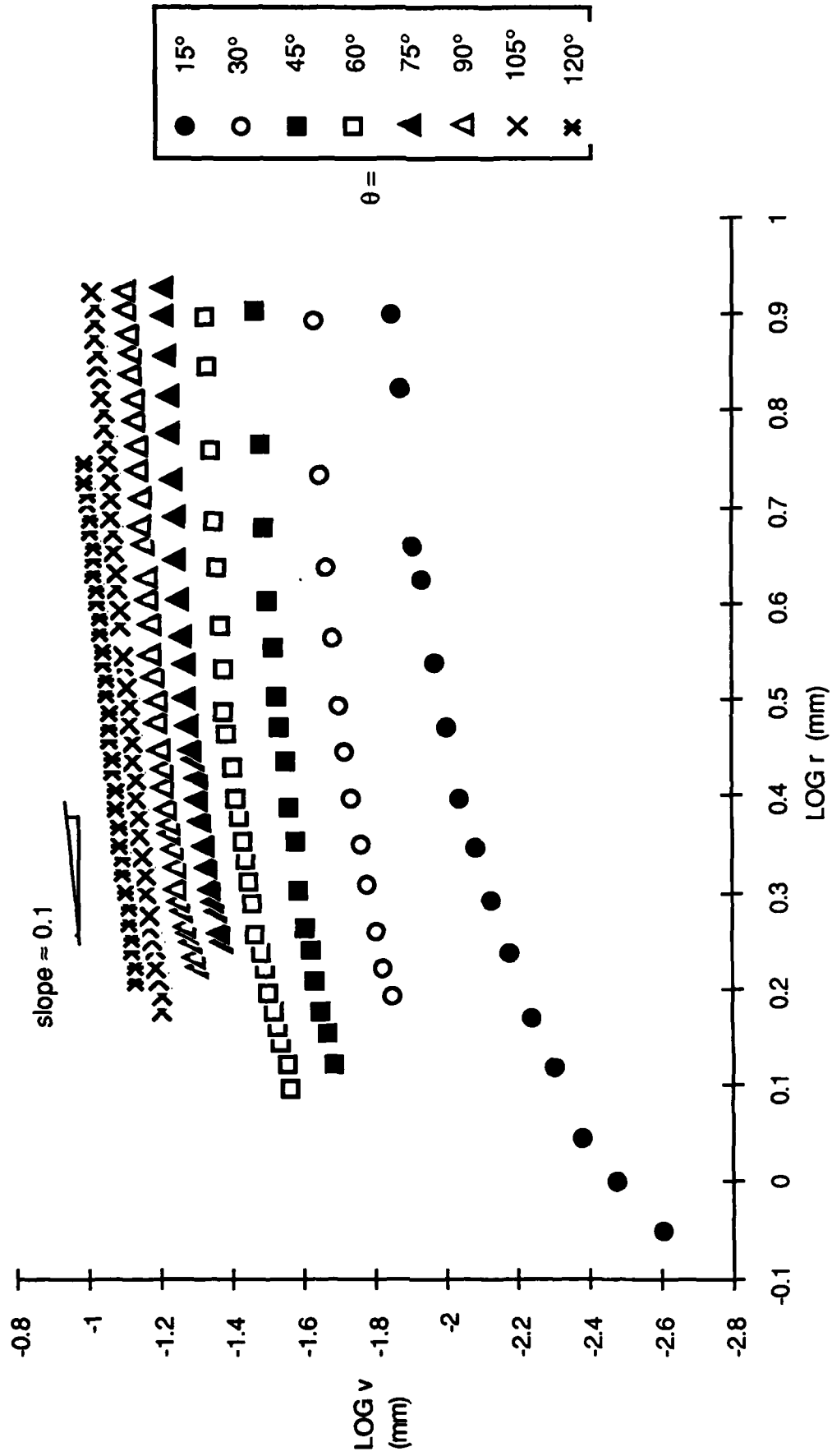


Figure 9 Log v Versus Log r Plots of 2024-T3 Aluminum SEN Specimen MD101987-8, B=2.

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