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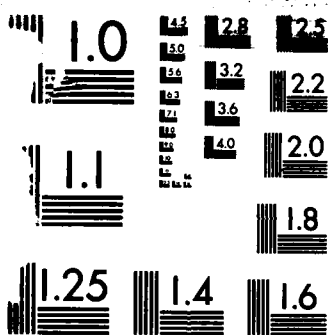
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TECHNICAL REPORT NO. ARCCB-TR-86001

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J<sub>Ic</sub> TESTING USING ARC-TENSION SAMPLES

J. A. KAPP

W. J. BILINSKY

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER  
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARCCB-TR-86001	2. GOVT ACCESSION NO. AD-A165788	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) J <sub>Ic</sub> TESTING USING ARC-TENSION SAMPLES		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J. A. Kapp and W. J. Bilinsky (see reverse)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Armament Research & Development Center Benet Weapons Laboratory, SMCAR-CCB-TL Watervliet, NY 12189-4050		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No. 6111.02.H600.011 PRON No. 1A425M541A1A
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research & Development Center Close Combat Armaments Center Dover, NJ 07801-5001		12. REPORT DATE January 1986
		13. NUMBER OF PAGES 19
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)  UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES  Presented at the 17th National Fracture Mechanics Symposium, Albany, NY, 7-9 August 1984. Published in Proceedings of the Symposium.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) J <sub>Ic</sub> Testing Alternate Specimens J Analysis Fracture Mechanics Arc-Shaped Specimens		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) J <sub>Ic</sub> was determined in two materials (6061-T651 aluminum and ASTM A-723 grade 1, class 4 pressure vessel steel) using arc-tension (A(T)) and compact tension (C(T)) samples. The J-R curves were determined by using both the multispecimen method and the compliance unloading method. J was determined for the A(T) specimen by the Merkle-Corten method of analysis as modified by Clarke and Landes. A correction factor was included to account for the tensile loading (CONT'D ON REVERSE)		

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20. ABSTRACT (CONT'D)

component, and both the plastic and elastic components of J were necessary when using the A(T) sample. With the proper formulas for J in the A(T) sample, the same J-R curves were determined in both materials using either A(T) or C(T) samples. This preliminary study suggested that the A(T) sample was totally adequate for  $J_{Ic}$  testing and should be included in subsequent versions of ASTM Method E-813 on  $J_{Ic}$ , A Measure of Fracture Toughness.

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## INTRODUCTION

Fracture toughness, whether measured as  $K_{Ic}$  or  $J_{Ic}$  is a valuable measurement of a material's tolerance of pre-existing defects and many engineering applications. The present method for determining  $J_{Ic}$  (ASTM Method E-813 on  $J_{Ic}$ , A Measure of Fracture Toughness) allows  $J_{Ic}$  to be measured by either a compact tension (C(T)) sample or a three-point bend sample (SE(B)). Sometimes it is difficult to obtain specimens of these geometries from certain structural components such as cylindrical pressure vessels. The arc-tension (A(T)) sample is easily obtained from such cylindrical components. This report summarizes the results of an initial study into the feasibility of using A(T) samples for  $J_{Ic}$  testing.

## CALCULATION OF J FOR A(T) SAMPLES

The A(T) sample (Figure 1) encompasses a large range of possible geometries. This is due to the variability of  $R_2$ ,  $R_1$ , and  $X$ . For this sample to be of the most use, restrictions on  $R_2$  and  $R_1$  cannot be allowed, but restricting  $X$  in J testing should cause few difficulties.  $X$  is made variable in K testing mainly for load efficiency, but if substantial plasticity is allowed as in J testing, load efficiency is not as important. Thus, we restrict our thinking to A(T) samples with  $X = 0$ , which has the further experimental advantage in displacement measurement as the load line intersects the crack mouth.

To determine  $J$  for the arc-tension sample, we proceed in the manner outlined by Merkle and Corten (ref 1) as modified by Clarke and Landes (ref 2). Under fully plastic conditions on the uncracked ligament, the load-displacement trace is idealized as shown in Figure 2, and  $J$  is (Equation 9, Reference 2):

$$\begin{aligned}
 J = & \frac{2}{bB} \left[ \frac{1+\alpha}{1+\alpha^2} - \alpha \frac{(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2} \right] A_T \\
 & + \frac{2\alpha}{bB} \frac{(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2} P^* \delta_T + G \\
 & - \frac{2}{bB} \left[ \frac{1+\alpha}{1+\alpha^2} + \alpha \frac{(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2} \right] A_e \quad (1)
 \end{aligned}$$

where  $b$  and  $B$  are as shown in Figure 1;  $A_T$ ,  $P^*$ ,  $\delta_T$  and  $A_e$  are from Figure 2;  $G$  is the elastic energy release rate, and

$$\alpha = 2((a/b)^2 + a/b + 1/2)^{1/2} - 2(a/b + 1/2) \quad (2)$$

where  $a$  is the crack length as shown in Figure 1.

Equation (1) is too cumbersome to be useful experimentally. The first step in simplifying the equation is to assume that the higher order terms involving  $A_T$  and  $P^*\delta_T$  cancel:

$$J = \frac{2A_T}{bB} \frac{1+\alpha}{1+\alpha^2} + G - \frac{2A_e}{bB} \left[ \frac{1+\alpha}{1+\alpha^2} + \frac{\alpha(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2} \right] \quad (3)$$

It is convenient to represent  $G$  in terms of the elastic area  $A_e$ . It can be shown that (refs 1,2):

<sup>1</sup>Merkle, J. G. and Corten, H. T., J. of Pressure Vessel Technology, Trans. ASME, Vol. 96, November 1974, pp. 286-292.

<sup>2</sup>Clarke, G. A. and Landes, J. D., Journal of Testing and Evaluation, Vol. 7, No. 5, September 1979, pp. 264-269.

$$G = \left[ \frac{k(1-a/w)Y^2}{EB} \right] \frac{2A_e}{Bb} \quad (4)$$

where

$$Y = \frac{KB\sqrt{w}}{P}$$

and  $k$  is the elastic stiffness of the specimen or the initial slope of the load-displacement record,  $K$  is the stress intensity factor, and  $E$  is the elastic modulus. Finally, we can write Eq. (3) in the simple form

$$J = \lambda_1 \frac{2A_T}{Bb} + \lambda_2 \frac{2A_e}{Bb} \quad (5)$$

$$\lambda_1 = \frac{1+\alpha}{1+\alpha^2} \quad (6)$$

$$\lambda_2 = \frac{k(1-a/w)Y^2}{EB} - \left( \lambda_1 + \frac{\alpha(1-2\alpha-\alpha^2)}{(1-\alpha^2)\alpha^2} \right) \quad (7)$$

These equations are the same equations that were developed for the C(T) sample (refs 1,2). However, in the C(T) sample when  $a/w$  is 0.5 or larger,  $\lambda_2$  is negligible. This is not the case with the arc-tension sample. We evaluate  $\lambda_2$  by using wide-range expressions fit to numerical stress analysis results (refs 3,4).

<sup>1</sup>Merkle, J. G. and Corten, H. T., J. of Pressure Vessel Technology, Trans. ASME, Vol. 96, November 1974, pp. 286-292.

<sup>2</sup>Clarke, G. A. and Landes, J. D., Journal of Testing and Evaluation, Vol. 7, No. 5, September 1979, pp. 264-269.

<sup>3</sup>Kapp, J. A., Newman, J. C., Jr., and Underwood, J. H., Journal of Testing and Evaluation, Vol. 8, No. 6, November 1980, pp. 314-317.

<sup>4</sup>Kapp, J. A., Leger, G. S., and Gross, Bernard, "Wide Range Displacement Expressions for Standard Fracture Toughness Specimens," Fracture Mechanics: 16th Symposium, (M. F. Kanninen and A. T. Hopper, eds.), ASTM STP 868, ASTM, Philadelphia, PA, 1985.

$$Y = \frac{KB\sqrt{w}}{P} = [3 x/w + 1.9 + 1.1 a/w][1 + 0.25(1 - a/w)^2(1-R_1/R_2)]f(a/w) \quad (8)$$

$$f(a/w) = ((a/w)^{1/2}/(1-a/w)^{3/2})(3.74 - 6.30 a/w + 6.32(a/w)^2 - 2.43(a/w)^3)$$

$$k = \frac{P}{\delta} = \frac{EB(1-a/w)^2}{(2 x/w + 1 + a/w)F(a/w, r_1/r_2)} \quad (9)$$

$$F(a/w, R_1/R_2) = [0.34 + 13.75 a/w - 12.67(a/w)^2 + 6.47(a/w)^2 + (1-a/w)^{0.05}(1-R_1/R_2)(0.8-0.5 R_1/R_2)]$$

To compare the quantities necessary to determine J, it is convenient to use the following notation:

$$\lambda_1 = \frac{1+\alpha}{1+\alpha^2}$$

$$\lambda^* = \frac{\alpha(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2}$$

$$\lambda_J = \lambda_1 + \lambda^*$$

$$\lambda_e = \frac{k(1-a/w)Y^2}{EB}$$

These quantities are computed for various  $R_1/R_2$  and comparisons made in Table I. The tabulation shows that in the crack length range important to  $J_{IC}$  testing  $a/w > 0.45$ ,  $\lambda_2$  is not negligible. Indeed, should  $A_e$  be a significant portion of  $A_T$ , neglecting to account for this elastic portion of J would introduce errors approaching 20 percent. Therefore, unlike  $J_{IC}$  testing with C(T) samples, we must include the contribution of  $A_e$  to obtain an accurate measurement of J when using A(T) specimens.

TABLE I. COMPARISON OF THE QUANTITIES USED TO DETERMINE J  
FOR THE ARC-TENSION,  $X/W = 0$  SAMPLE

$R_1/R_2 = 0.91$						
$a/w$	$\lambda_1$	$\lambda^*$	$\lambda_J$	$\lambda_e$	$\lambda_e/\lambda_J$	$\lambda_2$
0.3000	1.1773	0.0963	1.2736	1.8404	1.4450	0.5668
0.3500	1.1674	0.1013	1.2687	1.7164	1.3528	0.4476
0.4000	1.1565	0.1034	1.2600	1.6092	1.2772	0.3492
0.4500	1.1448	0.1029	1.2477	1.5183	1.2169	0.2706
0.5000	1.1325	0.1000	1.2325	1.4423	1.1703	0.209
0.5500	1.1196	0.0950	1.2146	1.3793	1.1356	0.1647
0.6000	1.1063	0.0882	1.1946	1.3271	1.1110	0.1326
0.6500	1.0929	0.0800	1.1728	1.2835	1.0944	0.1107
0.7000	1.0793	0.0705	1.1498	1.2459	1.0837	0.0962
0.7500	1.0657	0.0600	1.1257	1.2120	1.0766	0.0863
0.8000	1.0522	0.0488	1.1009	1.1790	1.0709	0.0780
$R_1/R_2 = 0.67$						
$a/w$	$\lambda_1$	$\lambda^*$	$\lambda_J$	$\lambda_e$	$\lambda_e/\lambda_J$	$\lambda_2$
0.3000	1.1773	0.0963	1.2736	1.8850	1.4800	0.6114
0.3500	1.1674	0.1013	1.2687	1.7501	1.3794	0.4814
0.4000	1.1565	0.1034	1.2600	1.6332	1.2962	0.3732
0.4500	1.1448	0.1029	1.2477	1.5338	1.2293	0.2861
0.5000	1.1325	0.1000	1.2325	1.4505	1.1769	0.2182
0.5500	1.1196	0.0950	1.2146	1.3814	1.1373	0.1668
0.6000	1.1063	0.0882	1.1946	1.3241	1.1085	0.1296
0.6500	1.0929	0.0800	1.1728	1.2763	1.0883	0.1035
0.7000	1.0793	0.0705	1.1498	1.2355	1.0746	0.0857
0.7500	1.0657	0.0600	1.1257	1.1991	1.0652	0.0734
0.8000	1.0522	0.0488	1.1009	1.1644	1.0576	0.0634

TABLE I. COMPARISON OF THE QUANTITIES USED TO DETERMINE J  
FOR THE ARC-TENSION,  $X/W = 0$  SAMPLE (CONT'D)

$R_1/R_2 = 0.5$						
$a/w$	$\lambda_1$	$\lambda^*$	$\lambda_J$	$\lambda_e$	$\lambda_e/\lambda_J$	$\lambda_2$
0.3000	1.1773	0.0963	1.2736	1.8987	1.4908	0.6251
0.3500	1.1674	0.1013	1.2687	1.7591	1.3865	0.4904
0.4000	1.1565	0.1034	1.2600	1.6375	1.2997	0.3776
0.4500	1.1448	0.1029	1.2477	1.5339	1.2294	0.2862
0.5000	1.1325	0.1000	1.2325	1.4469	1.1740	0.2145
0.5500	1.1196	0.0950	1.2146	1.3746	1.1318	0.1600
0.6000	1.1063	0.0882	1.1946	1.3147	1.1006	0.1201
0.6500	1.0929	0.0800	1.1728	1.2648	1.0784	0.0919
0.7000	1.0793	0.0705	1.1498	1.2223	1.0631	0.0725
0.7500	1.0657	0.0600	1.1257	1.1846	1.0524	0.0590
0.8000	1.0522	0.0488	1.1009	1.1493	1.0439	0.0484
$R_1/R_2 = 0.4$						
$a/w$	$\lambda_1$	$\lambda^*$	$\lambda_J$	$\lambda_e$	$\lambda_e/\lambda_J$	$\lambda_2$
0.3000	1.1773	0.0963	1.2736	1.9007	1.4923	0.6270
0.3500	1.1674	0.1013	1.2687	1.7593	1.3867	0.4906
0.4000	1.1565	0.1034	1.2600	1.6357	1.2982	0.3757
0.4500	1.1448	0.1029	1.2477	1.5302	1.2263	0.2824
0.5000	1.1325	0.1000	1.2325	1.4414	1.1696	0.2090
0.5500	1.1196	0.0950	1.2146	1.3676	1.1260	0.1530
0.6000	1.1063	0.0882	1.1946	1.3064	1.0936	0.1118
0.6500	1.0929	0.0800	1.1728	1.2554	1.0704	0.0826
0.7000	1.0793	0.0705	1.1498	1.2121	1.0543	0.0624
0.7500	1.0657	0.0600	1.1257	1.1740	1.0429	0.0483
0.8000	1.0522	0.0488	1.1009	1.1385	1.0341	0.0375

Although  $\lambda_2$  could be calculated from Eqs. (8) and (9), significant computation is involved. Noting that  $\lambda_2$  is virtually independent of  $R_1/R_2$ , a simple polynomial in  $a/w$  can be found from which  $\lambda_2$  is more easily determined. Using least squares the polynomial is:

$$\lambda_2 = 1.919 - 6.235(a/w) + 6.935(a/w)^2 - 2.557(a/w)^3 \quad (10)$$

In the range of  $0.5 < a/w < 0.6$ , Eq. (10) agrees with the computed values of  $\lambda_2$  within about five percent for  $R_1/R_2$  between 0.4 and 0.9.

#### EXPERIMENTAL PROCEDURE

$J_{IC}$  tests were performed on a pressure vessel steel and an aluminum alloy using both A(T) and C(T) samples. Also, both methods for determining crack growth outlined in ASTM Method E-813 on  $J_{IC}$ , A Measure of Fracture Toughness, (compliance unloading and fracture surface measurement) were used. The aluminum alloy used was 6061-T651 supplied in rolled sheet form 0.5 inch (1.27 cm) thick. Specimens were obtained such that the L-T direction was tested. The compact tension samples were of the standard geometry with thickness (B) of 0.5 inch (1.27 cm). A(T) samples were produced such that the outside radius  $R_2$  was 2.0 inches (5.08 cm) and the inside radius  $R_1$  was 1.0 inch (2.54 cm). The pressure vessel steel used was ASTM A-723 grade 1, class 4. Specimens were obtained from a long hollow cylindrical forging which had an outside radius of 4.6 inches (11.7 cm) and an inside radius of 1.9 inches (4.8 cm). Samples were obtained in the C-R orientation with through thickness, B, dimension of 1.35 inches (3.4 cm). After testing the A(T) specimens, C(T) samples were machined from one of the broken halves of the A(T) sample. The largest possible sample was obtained, one with through thickness (B) of 0.8 inch (2.3 cm).

## RESULTS AND DISCUSSION

The results of the testing of these samples appear in Figures 3 through 6. The results from the pressure vessel steel (Figures 3 and 4) suggest very little difference in  $J_{IC}$  by using different samples. With the multispecimen method (Figure 3), the slope of the resistance curve is the same for either sample, but the intersection with the blunting line is somewhat greater when using compact tension samples. Although  $J_{IC}$  appears to be affected by the specimen, the difference between the two test results can be easily attributed to scatter. With compliance unloading (Figure 4), more variation is evident. The two resistance curves from the arc-tension samples are approximately parallel but offset such that different values of  $J_{IC}$  were obtained. Comparing these to the two curves generated using compact tension samples, we find that the least squares fit to these data gives a slope which is substantially steeper than those obtained with arc-tension samples. The  $J_{IC}$  values obtained from these tests are very close ( $76 \text{ kJ/m}^2$  and  $81 \text{ kJ/m}^2$ ) and compare very favorably with one of the two arc-tension sample  $J_{IC}$  measurements. Again, one might consider the differences as the result of using different specimen geometries, but it is safe to account for these differences as material scatter.

Comparing the results of testing the 6061-T651 aluminum alloy also shows little or no difference between arc-tension and compact tension samples. With multispecimen testing (Figure 5), essentially the same resistance curve was obtained using either sample geometry. The least squares lines fit to these data gives a small difference in slope and somewhat different  $J_{IC}$  value, but again these differences are material property scatter. With compliance

unloading, similar to the steel results, more scatter was observed. All of the resistance curves had essentially the same slopes, but  $J_{IC}$  varied a great deal with these specimens. The two compact tension  $J_{IC}$  values agreed very well, but the two arc-tension samples differed substantially, although the average of the two compact tension values compared very well with the average of the two arc-tension values.

For further comparison, the  $J_{IC}$  results are presented in Table II. For each material and specimen type, the three  $J_{IC}$  values generated (one by the multispecimen method and two by the compliance unloading method) are treated as a single statistical population. The mean value and standard deviation are given for each population. It is clear that the mean value of  $J_{IC}$  from the A(T) and C(T) specimens of pressure vessel steel is essentially the same, although there seems to be somewhat more scatter generated when the A(T) specimens are used. The reason for the scatter cannot be established at this time. Further testing would be required to determine if the difference is due to specimen geometry or natural material scatter. The same can be stated for the aluminum. Reasonable agreement between the mean values of  $J_{IC}$  from either specimen type was observed, but as in the case of the aluminum tests, scatter is much greater when A(T) samples are used than when C(T) samples are used. Again, whether the cause of the scatter is the specimen geometry or material related, it would have to be determined by testing a larger number of specimens.

Regardless of the reasons for increased scatter in the  $J_{IC}$  results from A(T) samples versus C(T) samples, it is encouraging that the mean values of  $J_{IC}$  for two different materials are about the same using both A(T) and C(T)

samples. Further testing should be performed, perhaps in coordination with Task Group E24.08.04 as a laboratory round robin to establish if the A(T) sample should be included in later versions of ASTM Method E-813 on  $J_{IC}$ , A Measure of Fracture Toughness.

TABLE II. STATISTICAL COMPARISON OF  $J_{IC}$  MEASURED WITH BOTH A(T) AND C(T) SAMPLES

Material	$J_{IC}$ (kJ/m <sup>2</sup> )		
	A(T)	C(T)	
Pressure Vessel Steel	75	86	
	94	76	
	<u>79</u>	<u>81</u>	
	Mean	82.6	81.0
	Standard Deviation	10.0	5.0
6061-T651 Aluminum	7.9	9.4	
	5.5	8.6	
	<u>16.1</u>	<u>5.9</u>	
	Mean	9.8	8.0
	Standard Deviation	5.56	1.83

## SUMMARY AND CONCLUSIONS

Analyses and tests were performed to determine the applicability of using A(T) samples for  $J_{IC}$  testing. The analysis showed that to determine  $J$  for these specimens, a more involved calculation is necessary, namely,  $J$  must be broken into its elastic and plastic components. Two areas under the load displacement curve must be measured. This is more complex than the analysis involved with compact tension samples, but the additional amount of analysis involved should not restrict the use of A(T) samples.  $J_{IC}$  measurements were made using both compact tension and arc-tension samples. The A(T) sample should be considered as an alternative specimen in future versions of ASTM Method E-813 on  $J_{IC}$ , A Measure of Fracture Toughness.

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3. Kapp, J. A., Newman, J. C., Jr., and Underwood, J. H., Journal of Testing and Evaluation, Vol. 8, No. 6, November 1980, pp. 314-317.
4. Kapp, J. A., Leger, G. S., and Gross, Bernard, "Wide Range Displacement Expressions for Standard Fracture Toughness Specimens," Fracture Mechanics: 16th Symposium, (M. F. Kanninen and A. T. Hopper, eds.), ASTM STP 868, ASTM, Philadelphia, PA, 1985.

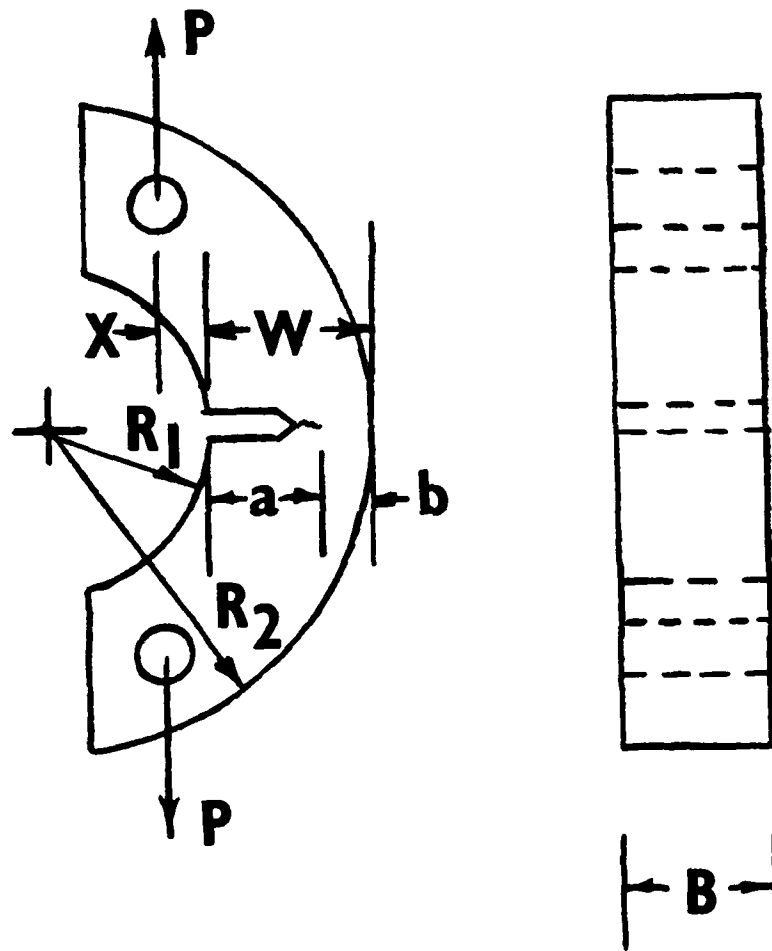


Figure 1. The arc-tension sample.

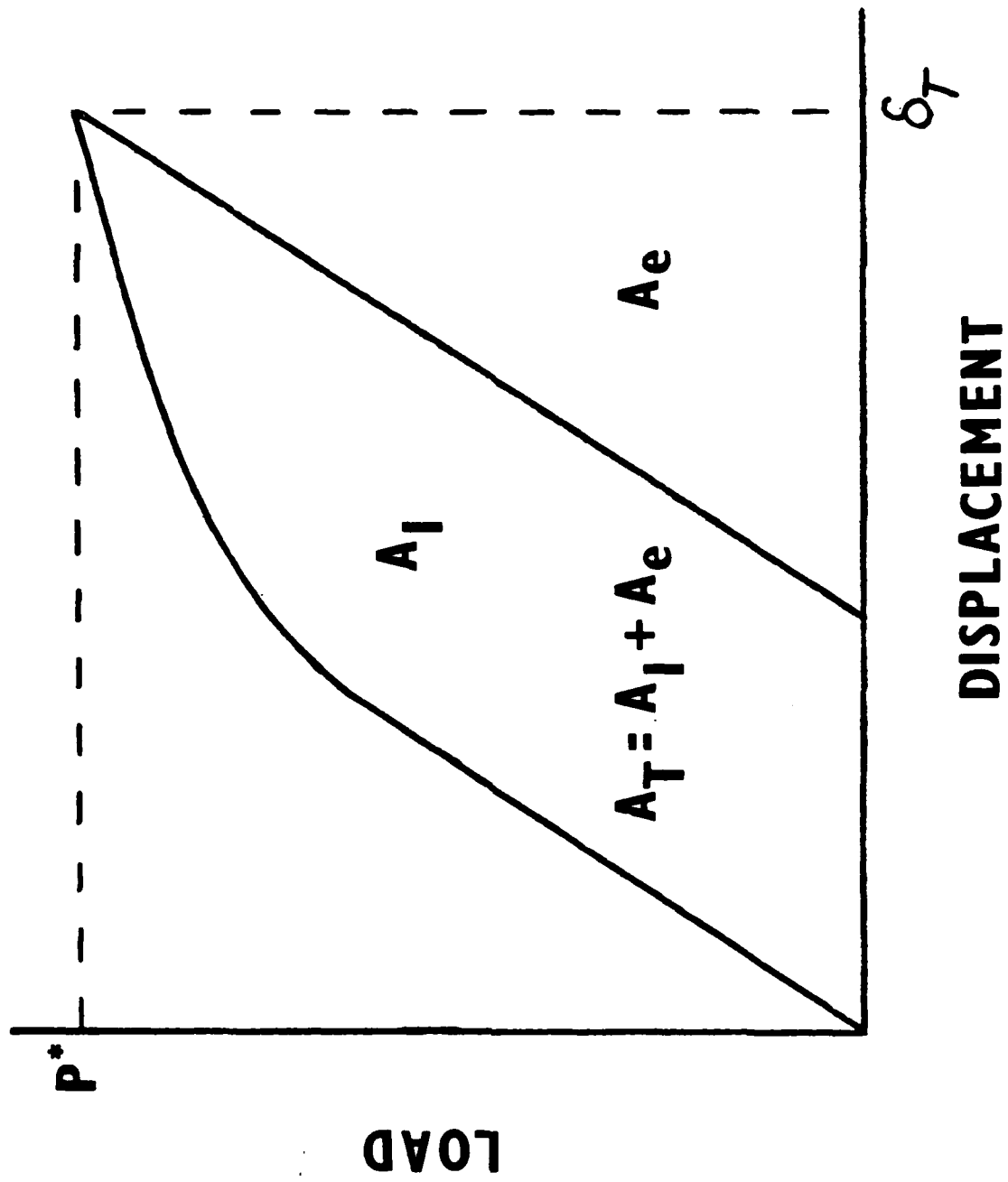


Figure 2. Idealized elastic-plastic load-displacement trace.

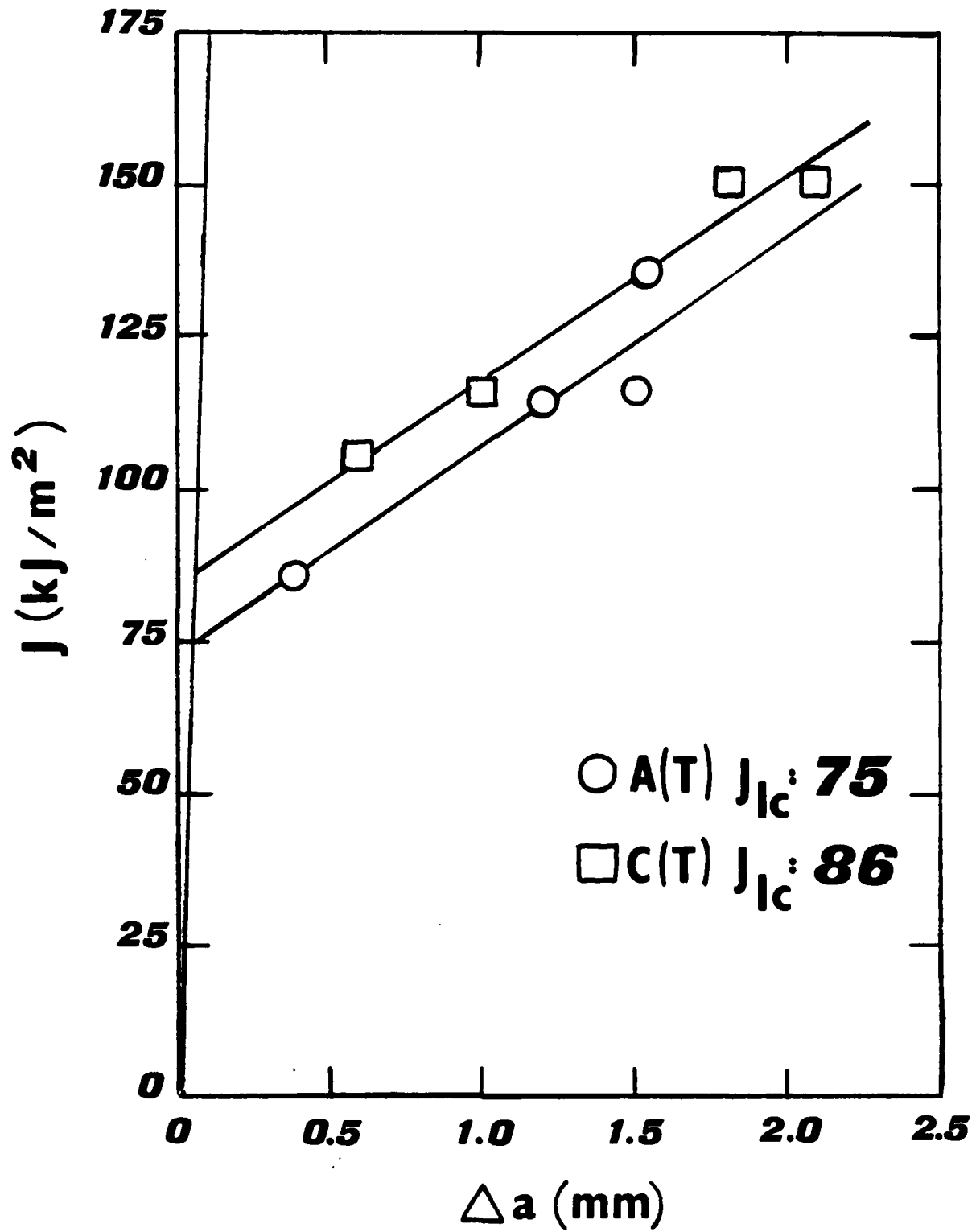


Figure 3. Multispecimen J-R curves for A-723 pressure vessel steel.

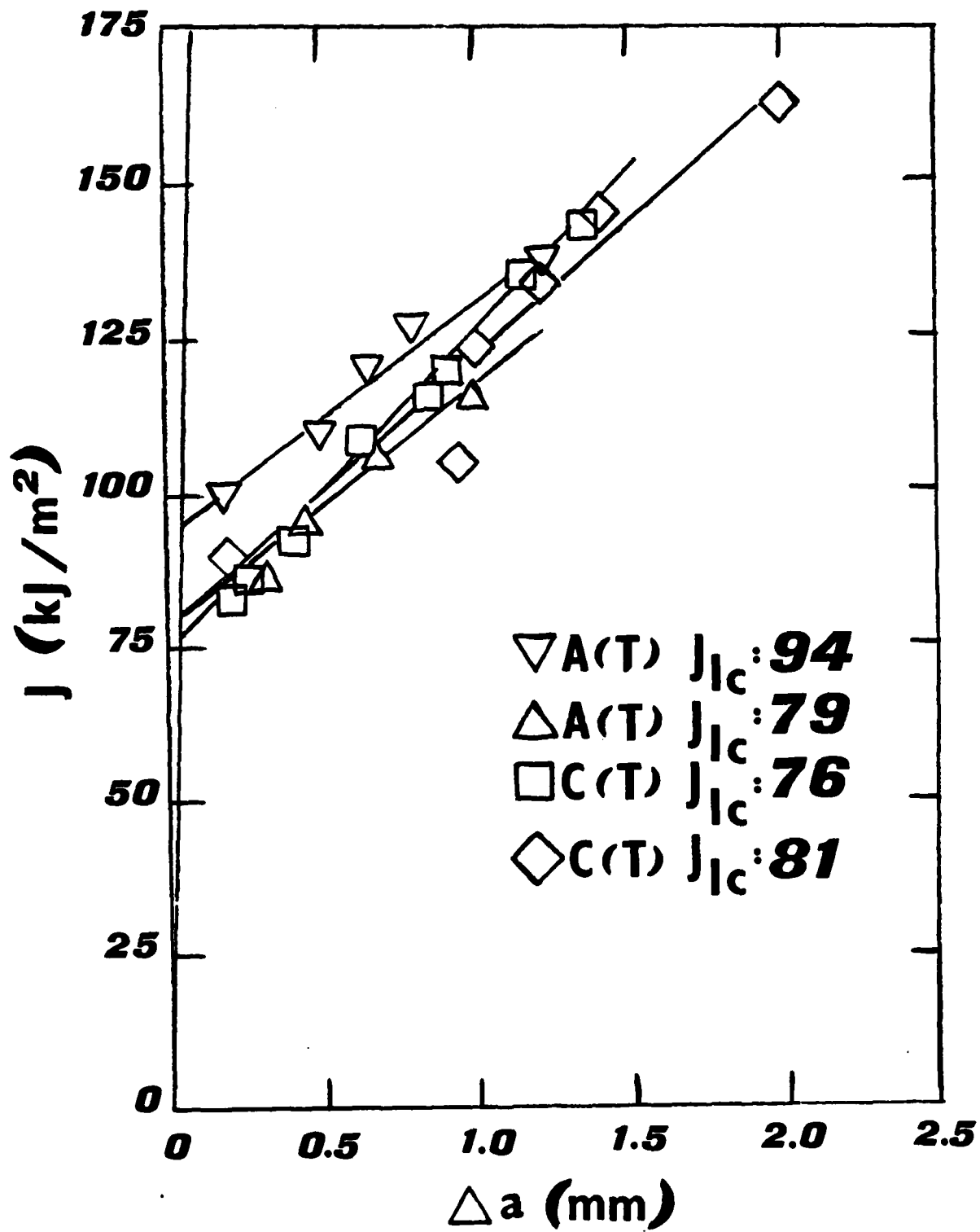


Figure 14. Compliance unloading J-R curves for A-723 pressure vessel steel.

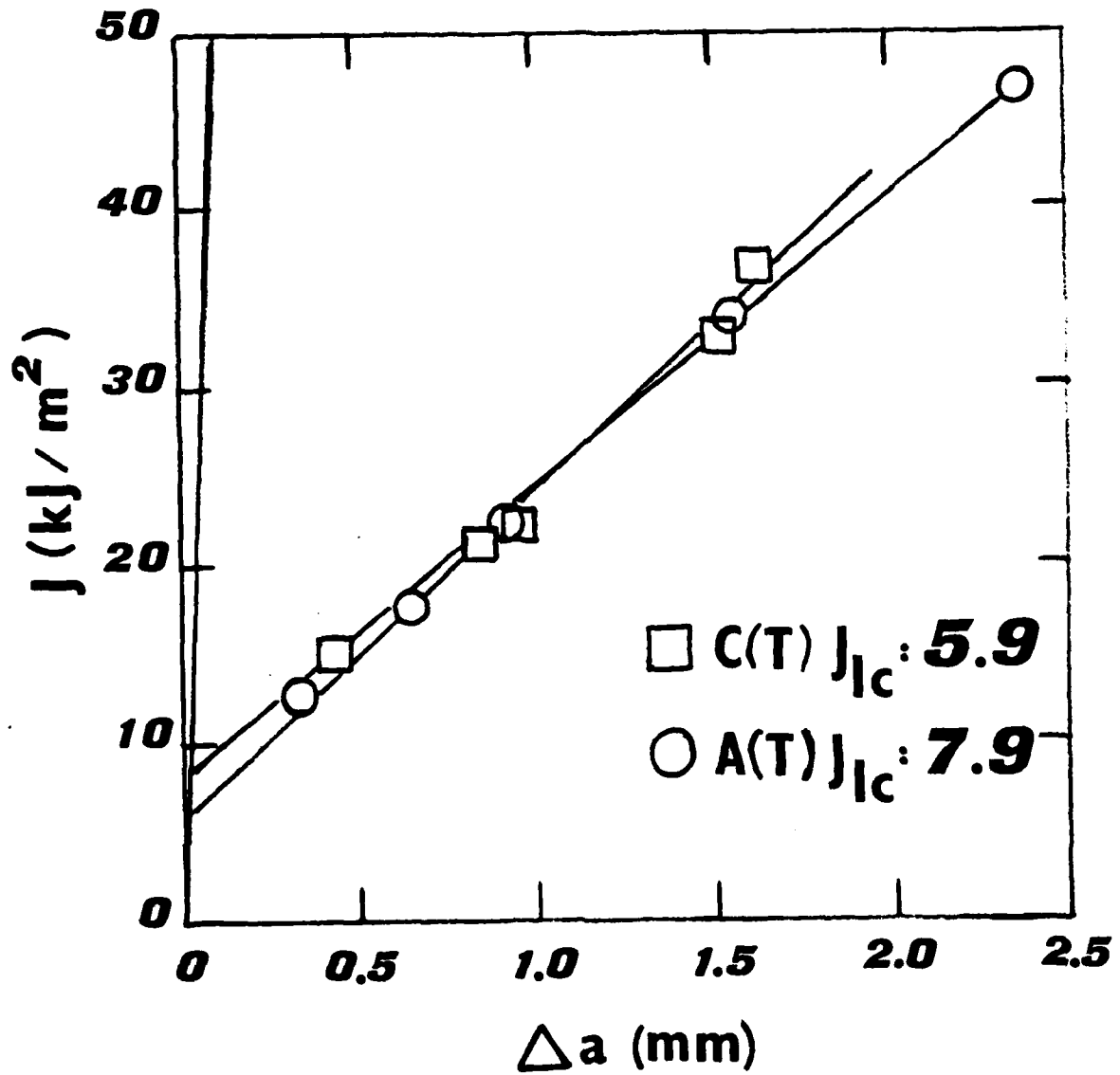


Figure 5. Multispecimen J-R curves for 6061-T651 aluminum.

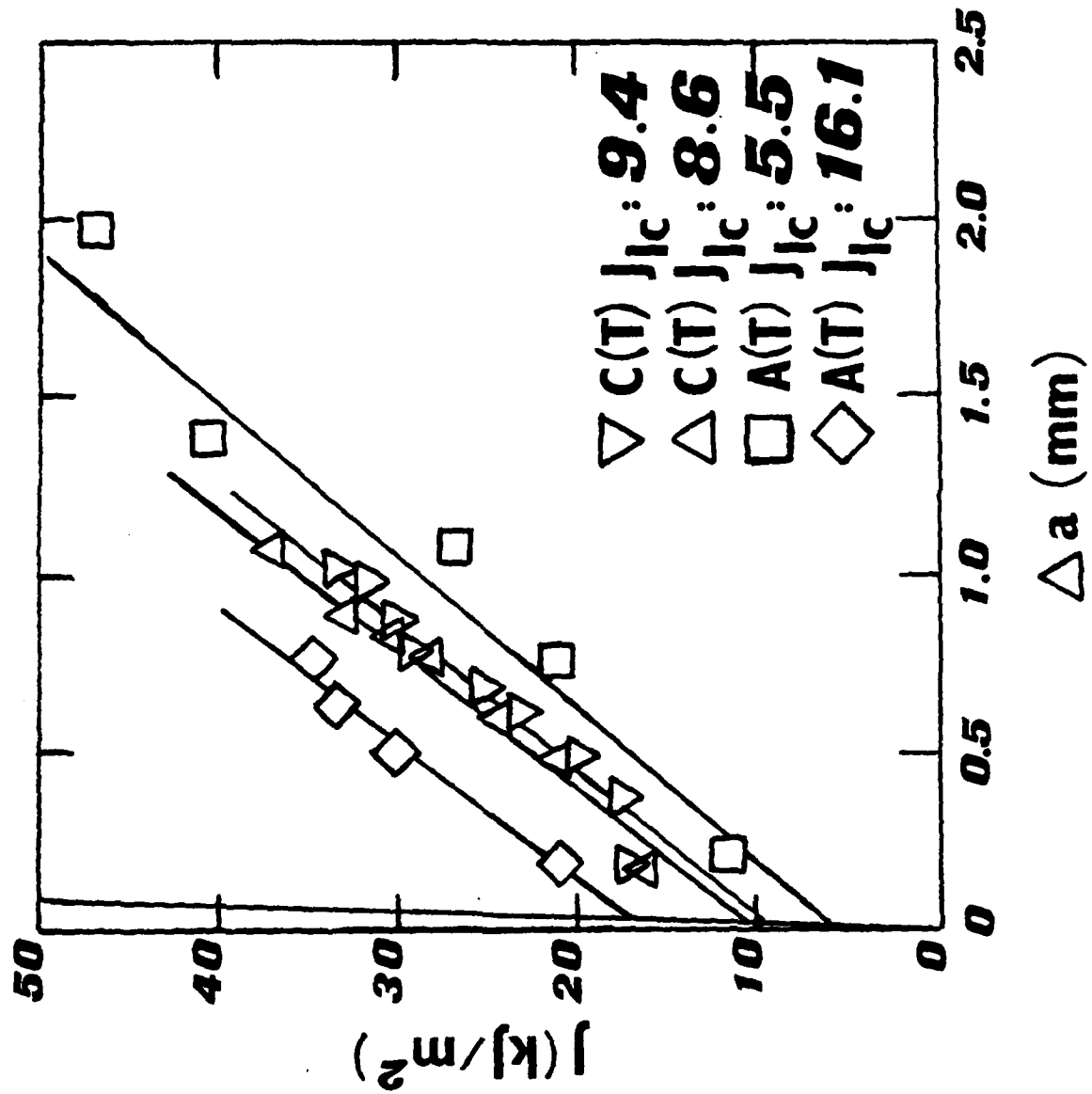


Figure 6. Compliance unloading J-R curves for 6061-T651 aluminum.

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