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THE EFFECT OF CRACK LENGTH AND SIDE GROOVES ON THE DUCTILE FRACTURE TOUGHNESS PROPERTIES OF ASTM A533 STEEL

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ABSTRACT

The ductile fracture toughness, J_{IC}, and tearing modulus, T, of ASTM A533, Grade B, Class 1 steel were evaluated by the urloading compliance method for determining J-R curves. These properties were measured for a matrix of 1T specimens in which the relative crack length, a/W, and the depth of side grooving were systematically varied to determine their individual effects. In addition, the applicability of an LVDT extensometer system was investigated for use in the unloading compliance method for J-R curve determination.

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CONTENTS

		Page
	Abstract	ii
	Acknowledgements	iv
	Figures	vi
	Tables	viii
	Foreword	i>
	Definitions	XV
	Conversions	XV
Ι.	SUMMARY AND CONCLUSIONS	1
Π.	INTRODUCTION	3
	A. BACKGROUND	3
	B. SCOPE	4
III.	EXPERIMENTAL PROCEDURE	5
	A. MATERIAL	5
	B. TESTING AND ANALYSIS	6
IV.	RESULTS AND DISCUSSION	13
	A. J-R CURVE RESULTS FROM THE BASELINE ANALYSIS	13
	B. J-R CURVE RESULTS USING THE LVDT EXTENSOMETER SYSTEM	29
	C. RECOMMENDED FUTURE WORK	48
V	DEEEDENCES	51

FIGURES

Figur	re	Page
1	Side Grooved 1T CT Specimen	7
2	Dual LVDT and Clip Gage (CG) Extensometers Mounted on a Compact Specimen	9
3	Schematic Representation of the R-Curve Analysis	11
4	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-47 $(a/W = 0.5, \% SG = 0)$	16
5	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-34 $(a/W = 0.5, \% SG = 10)$	17
6	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-36 $(a/W = 0.5, \% SG = 20)$	18
7	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-143 $(a/W = 0.6, \% SG = 0)$	19
8	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-38 $(a/W = 0.6, \% SG = 10)$	20
9	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-40 $(a/W = 0.6, \% SG = 20)$	21
10	R-Curve from the Clip Gage for Matrix Specimen 02GA603 $(a/W = 0.7, \% SG = 0)$	22
11	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-41 $(a/W = 0.7, \% SG = 10)$	23
12	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-43 $(a/W = 0.7, \% SG = 20)$	24
13	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-28 $(a/W = 0.8, \% SG = 0)$	25
14	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-45 $(a/W = 0.8, \% SG = 10)$	26
15	R-Curve from the Clip Gage for Matrix Specimen 02GAA1-46 $(a/W = 0.8, \% SG = 20)$	27
16	Heat Tinted Fracture Surfaces for the Test Matrix Specimens	28

FIGURES (Cont'd)

Figu	ire	Page
17	Experimental LVDT Compliance Data from the Smooth Matrix Specimens (% SG = 0) with an Empirical 10th Order Poly- nomial Equation Fit Through the Initial Crack Length Data	31
18	Experimental Clip Gage Compliance Data from the Smooth Matrix Specimens (% SG = 0) Compared with the Saxena- Hudak Relationship	32
19	R-Curve for Specimen 02GAA1-47 ($a/W = 0.5$, % SG = 0) from the LVDT	36
20	R-Curve for Specimen 02GAA1-34 ($a/W = 0.5$, % SG = 10) from the LVDT	37
21	R-Curve for Specimen 02GAA1-36 ($a/W = 0.5$, % SG = 20) from the LVDT	38
22	R-Curve for Specimen 02GAA1-143 $(a/W = 0.6, \% SG = 0)$ from the LVDT	39
23	R-Curve for Specimen 02GAA1-38 ($a/W = 0.6$, % SG = 10) from the LVDT	40
24	R-Curve for Specimen 02GAA1-40 ($a/W = 0.6$, % SG = 20) from the LVDT	41
25	R-Curve for Specimen 02GA603 ($a/W = 0.7$, % SG = 0) from the LVDT	42
26	R-Curve for Specimen 02GAA1-41 ($a/W = 0.7$, % SG = 10) from the LVDT	43
27	R-Curve for Specimen 02GAA1-43 ($a/W = 0.7$, % SG = 20) from the LVDT	44
28	R-Curve for Specimen 02GAA1-28 ($a/W = 0.8$, % SG = 0) from the LVDT	45
29	R-Curve for Specimen 02GAA1-45 ($a/W = 0.8$, % SG = 10) from the LVDT	46
30	R-Curve for Specimen 02GAA1-46 ($a/W = 0.8$, % SG = 20) from the LVDT	47

TABLES

Ta	ble	2	Page
	1	Chemical Composition of ASTM A 533-B1 Steel (HSST Plate 02)	5
	2	Strength and Impact Mechanical Properties of ASTM A533-B1 Steel at 149°C (300°F)	5
	3	J-R Curve Results From the Clip Gage Extensometer	14
	4	Comparison of Computed and Measured Crack Lengths Based on Clip Gage Extensometer Results	15
	5	J-R Curve Results Based on Experimental Compliance Relationship for the LVDT	34
	6	Comparison of Computed and Measured Crack Lengths Based on the Experimental Compliance Equation for the LVDT Results	35

FOREWORD

The Heavy Section Steel Technology (HSST) Program is a United States Nuclear Regulatory Commission (NRC) sponsored effort coordinated by the Oak Ridge National Laboratory (ORNL) with G. D. Whitman as the HSST Program Manager.

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DEFINITIONS

a	Crack length
a _o	Initial crack length
°f	Final crack length
∆a	Crack extension
A	Area (energy) under a load-deflection record
b	Remaining uncracked ligament
В	Specimen thickness
С	Compliance
E	Modulus of elasticity
J	J-integral value
JIC	Critical J-integral value in the opening mode of fracture; ductile fracture toughness
T	Tearing modulus
W	Specimen width
σo	Uniaxial flow stress = $\frac{\sigma_{ys} + \sigma_{ts}}{2}$
°ys	Yield stress
ate	Tensile stress

CONVERSIONS

1 in. = 25.4 mm 1 lb = 4.448 N 1 lb/in.² = 6.894 x 10³ Pa 1 $\frac{\text{in.} \cdot \text{lb}}{\text{in.}^2}$ = 0.175 kJ/m²

THE EFFECT OF CRACK LENGTH AND SIDE GROOVES ON THE DUCTILE FRACTURE TOUGHNESS PROPERTIES OF

ASTM A533 STEEL

I. SUMMARY AND CONCLUSIONS

The objective of this investigation was to determine the effect of relative crack length (a/W) and depth of side grooving on the parameters obtained from a J-R curve; these parameters are J_{Ic} , dJ/da (slope), and T (tearing modulus). The J-R curves were developed using the single specimen unloading compliance technique. In so doing, assessment of the experimental procedures for conducting an unloading compliance J-R curve test was made. The following conclusions were drawn as a result of this investigation:

- As both a/W and the depth of side grooving increase, the degree of triaxiality through the thickness of the specimen at the crack tip increases. The resulting higher constraint tends to give straighter crack fronts with tunnelling reduced or eliminated.
- The slope of the crack extension line on the R-curve decreased as the depth of side grooving increased.
- 3) The physical location of each of the two extensometers on the test specimen was different and, thus, the compliance behavior of each extensometer separately was modeled by employing different compliance relationships. The Saxena-Hudak relationship was found to work quite satisfactorily for the clip gage location at the load-line on the crack plane. A tenth order polynomial was developed to model the LVDT behavior for its location mounted on the front face straddling the load-line.
- The compliance equations gave accurate predictions of the initial crack lengths where the crack fronts were relatively straight.

Final crack lengths were consistently underestimated because crack front tunnelling produced a deviation between the measured average crack length and that predicted by the compliance relationships. Therefore, the crack extension was consistently underestimated, but the magnitude of this difference decreased at higher a/W and % SG.

- 5) The R-curves developed from crack extension computed from the LVDT and clip gage compliances are different from one another for the same test. In some specimens, particularly those with smaller a/W and no side grooving, the difference was relatively large. For deeper cracks and side grooves, the differences were essentially negligible. The disparity between the R-curves developed from the clip gage and LVDT compliance is the subject of an ongoing investigation.
- 6) From the LVDT results, it is observed that J_{IC} generally decreases as a/W and depth of side grooving increase.

II. INTRODUCTION

A. BACKGROUND

In recent years a considerable effort has been expended on the development of a ductile fracture toughness criterion to characterize the fracture behavior of structural materials employed at temperatures where they exhibit elastic-plastic behavior. This effort has focused, to a large extent, on the J-integral, first proposed by Rice^(1,2) and later advanced as a failure criterion by Begley and Landes.^(3,4) Subsequently, methodology for Jintegral testing and analyses has evolved.⁽⁵⁻⁹⁾ However, the optimum procedures and analyses have yet to be conclusively defined and standardized.

The current recommended J-integral test procedure entails determining the critical plane strain J value, J_{Ic}, from the J-R curve, which is a plot of J as a function of crack extension, Δa . The most widely used method of obtaining a J-R curve is the multiple specimen, heat tint method where a number of identical specimens (usually five to ten) are loaded to various points on the load-deflection record corresponding to different amounts of crack extension. The specimen is unloaded, heat tinted in a furnace, and broken. The tinted crack extension can then be measured. This procedure, while generally considered reliable, has the disadvantage of requiring a number of specimens which greatly increases specimen costs, analysis time and, in the case of nuclear reactors, the amount of capsule space needed to irradiate numerous specimens. Hence, there is a need for a J-integral test requiring only a single specimen. A number of techniques for detecting the onset of crack extension were reported in the literature. (10-13) A promising procedure is the monitoring of instantaneous crack length (and, consequently, crack extension) by use of unloading compliance. In this procedure, the load-deflection test is interrupted at frequent intervals, unloaded a small amount (about 10-15% of the expected maximum load), and the compliance during the unloading accurately measured. The elastic compliance can be related to the crack length by experimentally established

relationships. Consequently, a change in compliance can be related to a change in crack length. Thus, during the course of a single test, J and $\triangle a$ can be monitored and used to produce an R-curve. Again, the optimum procedures and analysis for this technique need to be defined.

Another facet of J-integral testing that needs to be resolved is the effect of specimen size and geometry on the critical J value. To be a useful quantity, J_{IC} should be a material parameter. Thus, conditions must be established in which J_{IC} does not depend on size and geometry but represents plane strain conditions. Current recommended practice⁽⁹⁾ suggests these conditions are met when

B, b, a
$$\ge 25 \frac{J}{\sigma_0}$$

where:

B = thickness b = remaining uncracked ligament a = crack length σ_0 = flow stress = $\frac{\sigma_{ts} + \sigma_{ys}}{2}$ σ_{ts} = tensile stress σ_{vs} = yield stress (0.2% offset)

The adequacy of this size criterion requires additional confirmation.

B. SCOPE

The primary objective of this investigation was to determine the effects of relative crack length, a/W, and side grooving of the remaining ligament section on the J-R curve. Side grooving is of interest because it increases the degree of stress state triaxiality ahead of the crack tip, thus imposing a larger degree of plane strain behavior. Because of the desirability of a single specimen test for nuclear reactor applications, the unloading compliance technique was employed to generate the J-R curve. As a secondary objective, the development and applicability of a second extensometer system was studied. The reason for investigating the second extensometer is the need for a redundant measurement in the event that the primary extensometer fails during a test; also, a second system might prove more suitable for unloading compliance tests conducted in a hot cell.

III. EXPERIMENTAL PROCEDURE

A. MATERIAL

The material used in this investigation was ASTM A533, Grade B (A533-B1), Class 1 steel. The material was supplied by Oak Ridge National Laboratory under the auspices of the Heavy Section Steel Technology (HSST) Program. The A533-B1 material was removed from the HSST plate O2. The heat treatment for plate O2 consisted of normalizing at 913°C (1675°F), austenitizing at 871°C (1600°F), water quenching, temperating at 663°C (1225°F), and stress relieving at 607°C (1125°F). The chemical composition, given in Table 1, and the heat treatment were reported by Childress.⁽¹⁴⁾

TABLE 1

CHEMICAL COMPOSITION OF ASTM A533-B1 STEEL (HSST PLATE 02) (wt%)

<u>C</u>	Mn	Ni	Mo	Si	S	P	Cu	Fe
0.22	1.48	0.68	0.52	0.25	0.018	0.012	0.012	Balance

The specimens were removed from between the 1/4 and 3/4 thickness of the 30.48 cm (12 in.) plate. Mechanical properties ⁽¹⁵⁻¹⁷⁾ are given in Table 2. All specimens tested for this investigation were 2.54 cm (1T) compact specimens machined in the T-L orientation.

TABLE 2

STRENGTH AND IMPACT MECHANICAL PROPERTIES OF ASTM A533-B1 STEEL AT 149°C (300°F)

Yield Strength	=	434	MPa	(63,000 psi)
Ultimate Strength	=	579	MPa	(84,000 psi)
C _v Energy	=	126	joules	(93 ft-1b)
Modulus of Elasticity, E	=	2.1	$x 10^2$ GPa	(30.7 x 10 ⁶ psi)

B. TESTING AND ANALYSIS

As discussed previously, standard J-integral test procedures have not yet been established. Therefore, for this investigation, a set of guidelines for testing and analysis was agreed upon by a group of HSST contractors at a meeting in Annapolis, MD in September 1978. These guidelines were the basis for this investigation and are reviewed in this section. This will be referred to as the "baseline" analysis.

To systematically assess the effect of a/W and side grooving on the J-R curve, a test matrix was established varying a/W and the depth of side grooving. All specimens were IT compact specimens with varying notch depths so that after fatigue precracking, three specimens each had a/W values of 0.5, 0.6, 0.7 and 0.8. In each of these groups one specimen was left with smooth surfaces (0% side grooving), one was given 45° V-shaped side grooves to a total depth of 10% (5% on each side) of the thickness, and the third was given side grooves to a total depth of 20% of the thickness. The sketch in Figure 1 shows a side grooved specimen (the smooth specimens were identical except the side groove was not present). To insure consistently sharp crack tips, all specimens were precracked in fatigue at least 2.5 mm (0.100 in.) at loads low enough that plastic flow at the crack tips was minimized.

The fracture toughness tests were conducted at $149^{\circ}C$ ($300^{\circ}F$) where upper shelf behavior was observed. The temperature was controlled to approximately \pm 2°C in an air-circulating electrically-heated furnace. The specimen temperature was sensed with a thermocouple attached to the specimen surface. The IT specimens were brought to test temperature in the furnace and then allowed to soak at test temperature for at least an hour prior to testing.

A J-integral test requires an accurate load versus load-point deflection record. The tests were performed on an 89.0 kN (20,000 lb) capacity closedloop servo-controlled, hydraulic test system. The tests were conducted in stroke control at a rate of 0.5 mm (0.02 in.) per minute. Loading clevises



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in	ch	2-64
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a/W	В	a	b
. 50	1.00	1.00	1.00
.60	1.00	1.20	.80
.70	1.00	1.40	.60
.80	1.00	1.60	. 40

mm						
a/W	B	a	b			
.50	25.4	25.4	25.4			
.60	25.4	30.5	20.3			
.70	25.4	35.6	15.2			
.80	25.4	40.6	10.2			

HEDL 7906-063.25

FIGURE 1. Side Grooved 1T CT Specimen.

with flat bottom holes were used to test the compact specimens. The load was monitored by the system load cell. Two independent extensometer systems were used to measure displacement and provide redundancy in the event that one system failed during the test. Because of its widespread use and acceptance for J-integral testing, an electrical resistance clip gage (CG) served as the primary extensometer and was mounted on razor blade edges affixed to the crack notch at the load-line. The secondary extensometer was a linear variable differential transformer (LVDT) system, described elsewhere, (18) mounted on the front face and straddling the load-points on each side of the specimen. The signals from the LVDT's were added to give average load-line displacement measurements. The extensometer systems are shown in Figure 2.

To compute J for the compact specimens the formula developed by Rice, et al., (6) modified for the tensile component of load after Merkle and Corten, (19) and shortened by the ASTM Task Group E24.01.09, (9) was used. This equation is

$$J = \frac{2A}{Bb} \frac{(1 + \alpha)}{(1 + \alpha^2)}$$
(1)

where:

α =

$$\alpha = \left[\left(\frac{2a_{o}}{b}\right)^{2} + \frac{4a_{o}}{b} + 2\right]^{1/2} - \left(\frac{2a_{o}}{b} + 1\right)$$
(2)
A = area (energy) under the load deflection record

B = thickness (net section thickness for side grooved specimens)

= remaining uncracked ligament b

= initial crack length a

To compute crack length from the measured compliance, the compliance equation developed by Saxena and Hudak⁽²⁰⁾ for the load-line on the crack plane was used,

$$a/W = 1.000196 - 4.06319 U + 11.242 U2 - 106.043 U3 (3)+ 465.335 U4 - 650.677 U5$$



FIGURE 2. Dual LVDT and Clip Gage (CG) Extensometers Mounted on a Compact Specimen.

where: $U = \frac{1}{\sqrt{ECB} + 1}$ E = modulus of elasticity C = compliance

For a given specimen, the initial crack length was computed from the mean of ten compliance measurements at a low load level (about 25% of expected maximum load). Crack extension was computed by subtracting this value from the crack lengths computed from compliances measured during subsequent unloadings as the test progressed.

In order to determine the J_{IC} value, it was necessary to represent the crack tip blunting behavior and crack extension behavior. The intersection of the lines representing these two phenomena was taken as the J_{IC} value. The baseline analysis agreed upon was based on the procedures recommended in Reference 9. The blunting line was assumed to follow the theoretical relationship

> $\Delta a = J/2 \sigma_0$ (4)

The data points utilized for the construction of the crack extension line were those contained in an interval defined by lines parallel to the blunting line, Equation (4), but offset by 0.254 mm (0.010 in.) and 1.397 mm (0.055 in.) from the origin. The crack extension portion of the R-curve was constructed by a least squares linear regression through these points. This R-curve analysis is shown schematically in Figure 3.

After completion of a test, the specimen was heat tinted in a furnace at 649°C (1200°F) and then fractured after cooling in liquid nitrogen. The blue oxide coating clearly delineates the fatigue crack and crack extension; these quantities were measured at nine equally-spaced points along the crack front under a microscope with a vernier calibrated traveling stage at 48X magnification. The crack extension was taken as the mean of eight points: the seven interior measurements plus the average of the two surface measurements. The initial crack length as measured on the specimen fracture surface was used to compute the J values.



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FIGURE 3. Schematic Representation of the R-Curve Analysis.

To facilitate the intricate and complicated data acquisition and computation, a mini-computer system was used. The system consisted of a magnetic tape programmable computer, X-Y plotter, thermal printer, and a magnetic disk drive for data storage. The system was programmed to accurately record load . and displacements, compute the compliance, and assess the accuracy of compliance measurements. Real time computations of the compliance, the crack length, and the estimated J values were made and printed at the time of each unloading; all data were stored on a magnetic disk. Simultaneously, the X-Y recorder was autographically producing the load-deflection record. Upon completion of the test, the data from all the unloadings were assembled and plotted as a temporary J-R curve. After subsequent crack length measurements were made from the broken specimen, the data were recalled from the magnetic disk and more accurate J and Aa data were computed and plotted as a final J-R curve; these new data values were also stored on the magnetic disk. With all data permanently stored on the magnetic disks, the data were easily retrievable for subsequent analyses or replay.

All test recording and measurement equipment was calibrated to NBS traceable standards as a normal requirement. Test machines were checked for calibration prior to test. Extensometers were calibrated at test temperature and for a deflection range exceeding that required for the maximum deflection encountered during testing; for the extended ranges accuracy was better than one percent.

IV. RESULTS AND DISCUSSION

A. J-R CURVE RESULTS FROM THE BASELINE ANALYSIS

The intersection of the blunting line and crack extension line (see Figure 3) was defined as the onset of crack extension and the J value was attributed the J_{Ic} designation. Paris, et al.⁽²¹⁾ have proposed that the slope of the crack extension line is related to a parameter which describes stable crack extension; the "tearing modulus", T, is given by

$$T = \frac{dJ}{da} \cdot \frac{E}{\sigma_0^2}$$
(5)

where dJ/da = slope of the crack extension line. The J_{Ic} , dJ/da, and T results for this matrix of tests are given in Table 3. Table 4 summarizes the initial crack length, final crack length, and crack extension computed from the clip gage compliance and from direct measurement. The R-curve constructions are shown in Figures 4 through 15. Figure 16 shows the fracture surfaces of all specimens in the test matrix.

A significant observation, seen in Figure 16, is that the crack front becomes straighter with crack tunnelling reduced or eliminated as a/W and depth of side grooving (% SG) increase. This indicates that the through-the-thickness constraint increased with the greater depth of side grooving and also with increased crack length. As a result of the increased constraint, the slope of the R-curve, dJ/da, and, consequently, the tearing modulus, T, tended to decrease as the depth of side grooving increased; however, a consistent trend in dJ/da or T as a/W increased was not conclusively discernible. The J_{IC} results for these tests (Table 3) also do not show a distinct trend with either % SG or a/W but rather tend to vary over a large range. As shown in Table 4, the crack lengths computed from the elastic unloading compliance using the Saxena-Hudak relationship, Equation (3), for the initial fatigue cracks (straight crack fronts) were generally in good agreement with the direct nine-point measurement. Agreement after crack extension occurred was still good when crack fronts remained straight, but deteriorated when

TABLE 3

J-R CURVE RESULTS FROM THE CLIP GAGE EXTENSOMETER

	% Side Groove a/W	0%	10%	20%
0.5	a/W	0.527	0.519	0.515
	J _{Ic} , kJ/m ² (in-1b/in ²)	187.8 (1073)	242.0 (1383)	220.3 (1259)
	dJ/da, MPa (1b/in ²)	271 (39,239)	201 (29,159)	149 (21,572)
	T	215	160	118
).6	a/W	0.615	0.619	0.623
	J _{Ic} , kJ/m ² (in-1b/in ²)	395.2 (2258)	196.4 (1122)	253.0 (1446)
	dJ/da, MPa (1b/in ²)	175 (25,343)	228 (33,130)	142 (20,663)
	T	139	182	113
0.7	a/W	0.723	0.723	0.720
	J _{Ic} , kJ/m ² (in-1b/in ²)	350.0 (2000)	226.3 (1293)	184.3 (1053)
	dJ/da, MPa (1b/in ²)	198 (28,658)	217 (31,511)	170 (24,639)
	T	157	173	135
0.8	a/W	0.855	0.812	0.812
	J _{IC} , kJ/m ² (in-1b/in ²)	207.7 (1187)	215.1 (1229)	219.8 (1256)
	dJ/da, MPa (1b/in ²)	359 (52,116)	203 (29,389)	174 (25,185)
	T	286	161	138

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-	% SG	0	9	10	%	20	%
a/W		Meas	CG	Meas	CG	Meas	CG
	a	1.0530	1.0369	1.0387	1.0269	1.0290	1.0356
0.5	ar	1.1603	1.1198	1.1437	1.1308	1.1150	1.1272
	Δa	0.1073	0.0829	0.1050	0.1039	0.0860	0.0916
	a	1.2301	1.2328	1.2384	1.2371	1.2461	1.2570
0.6	36	1.3244	1.2990	1.3281	1.3101	1.3280	1.3355
	Δa	0.0943	0.0662	0.0897	0.0731	0.0819	0.0785
	a	1.4464	1.4481	1.4468	1.4481	1.4391	1.449
0.7	a	1.5467	1.5262	1.5291	1.5123	1.5083	1.5186
	Δa	0.1003	0.0781	0.0823	0.0642	0.0692	0.069
	a	1.7096	1.7112	1.6249	1.6309	1.6232	1.638
0.8	ar	1.7676	1.7503	1.7063	1.6961	1.7013	1.7079
	۵a	0.0580	0.0391	0.0814	0.0653	0.0781	0.069

COMPARISON OF COMPUTED AND MEASURED CRACK LENGTHS BASED ON CLIP GAGE EXTENSOMETER RESULTS



FIGURE 4. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-47 (a/W = 0.5, % SG = 0).



FIGURE 5. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-34 (a/W = 0.5, % SG = 10).



FIGURE 6. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-36 (a/W = 0.5, % SG = 20).



FIGURE 7. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-143 (a/W = 0.6, % SG = 0).



FIGURE 8. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-38 (a/W = 0.6, % SG = 10).



FIGURE 9. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-40 (a/W = 0.6, % SG = 20).



FIGURE 10. R-Curve from the Clip Gage for Matrix Specimen 02GA603 (a/W = 0.7, % SG = 0).



FIGURE 11. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-41 (a/W = 0.7, % SG = 10).



FIGURE 12. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-43 (a/W = 0.7, % SG = 20).



FIGURE 13. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-28 (a/W = 0.8, % SG = 0).



FIGURE 14. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-45 (a/W = 0.8, % SG = 10).



FIGURE 15. R-Curve from the Clip Gage for Matrix Specimen 02GAA1-46 (a/W = 0.8, % SG = 20).



FIGURE 16. Heat Tinted Fracture Surfaces for the Test Matrix Specimens.

crack extension manifested itself by crack front tunnelling near the midthickness of the specimen. The trends suggest that to obtain consistent plane strain ductile fracture toughness properties, it may be necessary to employ side grooves or perhaps deeper cracks.

The absence of consistent trends in these test results is believed to be the effect of shortcomings in the accepted data analysis procedures. Specifically, the applicability of the theoretical blunting line, Equation (4), as a model for the unloading compliance-based crack length during crack-openingstretch is questioned. This can be observed in the R-curves of Figures 4 through 15. In most of the R-curves, the experimental data points for the blunting portion of the R-curve do not lie on the theoretical blunting line, Equation (4). The reason is simply that Equation (4) yields a quantity which is a physical displacement at the crack tip due to local plastic deformation, while the compliance relationship, Equation (3), relates the elastic compliance with physical crack length. Thus, there seems to be no intrinsic reason for the apparent crack extension resulting from the crack tip blunting phenomenon to be quantitatively described by the elastic compliance measurement in the same way it is in the multiple specimen heat tint measurement. Some revisions in describing blunting as detected by the compliance method may be appropriate to effectively characterize the onset of crack extension. Alternatives for the blunting line described by Equation (4) will be studied in subsequent work.

B. J-R CURVE RESULTS USING THE LVDT EXTENSOMETER SYSTEM

The dual LVDT extensometer system described earlier was studied to assess its applicability for unloading compliance J-R curve tests. The LVDT system was intended to be a redundant extensometer in the event that the clip gage failed during the test of an irradiated specimen. However, if its applicability is demonstrated, it may eventually be used as the primary system because of its ease of use with manipulators in a hot cell compared to the clip gage. Good agreement between computed crack lengths from the LVDT and clip gage extensometers requires the use of compliance relationships appropriate for the specific extensometer location. The Saxena-Hudak relationship, Equation (3), was used with good results for the clip gage compliance data because it was compatible with clip gage location. As expected, the Saxena-Hudak relationship did not satisfactorily model the compliance behavior of the LVDT which was located on the front face.

To account for the location of the LVDT system, a separate compliance relationship was developed for the initial crack length data points from the LVDT; the clip gage results were still modeled by the Saxena-Hudak relationship. The LVDT data were fit to a tenth order polynomial given by

$$a/W = A + BU + CU^{2} + DU^{3} + EU^{4} + FU^{5} + GU^{6} + HU^{7}$$
(6)
+ IU⁸ + JU⁹ + KU¹⁰

where:

А	=	1.99703336	х	10 ⁻¹	G	=	-4.57086111	х	10-15
В	=	1.02757992	х	10 ⁻²	Н	=	3.20604500	х	10-18
С	=	-9.21439591	Х	10 ⁻⁵	I	=	-6.86811088	х	10-22
D		4.98545748	Х	10 ⁻⁷	J	=	-4.66766016	х	10-25
Е	=	-1.67770409	х	10 ⁻⁹	Κ	=	2.34185204	х	10 ⁻²⁸
F	=	3.54602681	x	10-12					

This relationship is valid in the interval $0.5 \le a/W < 0.86$ and provides a good fit for the initial crack length data as seen in Figure 17. This relationship was developed from data obtained from 1T specimens and as yet requires verification for other sizes.

In Figure 17, the experimental data points were plotted as normalized compliance, ECB, as a function of measured a/W (recall that the weighted ninepoint average measurement technique was used). To demonstrate the similarity of this relationship to the Saxena-Hudak relationship, Figure 18 shows the normalized clip gage crack length with the Saxena-Hudak relationship superimposed. In both figures, the initial and final crack lengths from the



FIGURE 17. Experimental LVDT Compliance Data from the Smooth Matrix Specimens (% SG = 0) with an Empirical 10th Order Polynomial Equation Fit Through the Initial Crack Length Data.



HEDL 7906-063.27

FIGURE 18. Experimental Clip Gage Compliance Data from the Smooth Matrix Specimens (% SG = 0) Compared with the Saxena-Hudak Relationship.

experimental data are plotted to observe the effect of crack tunnelling. To keep the comparison simple, only the data from smooth specimens (% SG = 0) were plotted. In both figures the initial measured crack lengths, where the crack fronts are relatively straight, show good agreement with their respective compliance equation. The final crack lengths deviate from the compliance relationships as the crack fronts bow out or tunnel. Therefore, the final crack lengths predicted from the compliance relationships are underestimated compared to the measured weight, nine-point average. Thus, it is apparent that after crack front tunn lling begins, the compliance relationships deteriorate as models for compl ance response to crack extension.

All LVDT extensometer data was analyzed using Equation (6). Table 5 summarizes the J_{IC} , dJ/da, and T results obtained from the LVDT extensometers. Initial crack length, final crack length, and crack extension for the LVDT extense and from the weighted nine-point average measurement are presented in Table 6. The R-curves developed from the LVDT data using the experimental compliance equation for the test matrix are shown in Figures 19 through 30.

Some trends were discernible from the data obtained from the LVDT extensometers. In general, J_{IC} decreases as a/W and % SG increase and dJ/da and T decrease as % SG increases (see Table 5). These observations, coupled with the increasingly straighter crack fronts observed as a/W and % SG increase, support the assertion that plane strain behavior is being approached as a/W and % SG increase. Table 6 shows that, similar to the clip gage, the crack length predicted by the compliance equation is in better agreement with the weighted nine-point average measured crack extension for the initial crack length where the crack front is relatively straight. In Figures 19 through 30, most of the R-curves, like those from the clip gage, reveal that the data points from the blunting portion of the R-curve do not lie on the theoretical blunting line, Equation (4).

While additional work is needed on the extensometer systems, the results reported herein indicate that the LVDT system modeled by the experimental

TABLE 5

J-R CURVE RESULTS BASED ON EXPERIMENTAL COMPLIANCE RELATIONSHIP FOR THE LVDT

	% Side Groove a/W	0%	10%	20%
0.5	a/W	0.527	0.519	0.515
	J _{Ic} , kJ/m ² (in-1b/in ²)	426.6 (2436)	322.1 (1839)	272.1 (1554)
	dJ/da, MPa (1b/in ²)	188 (27,327)	217 (31,515)	143 (20,694)
	T	150	173	113
0.6	a/W	0.615	0.619	0.623
	J _{Ic} , kJ/m ² (in-1b/in ²)	330.6 (1888)	314.0 (1793)	264.8 (1512)
	dJ/da, MPa (1b/in ²)	199 (28,819)	163 (23,637)	146 (21,150)
	T	158	130	116
0.7	a/W	0.723	0.723	0.720
	J _{Ic} , kJ/m ² (in-1b/in ²)	342.7 (1957)	272.3 (1555)	235.9 (1347)
	dJ/da, MPa (1b/in ²)	216 (31,398)	185 (26,904)	157 (22,828)
	T	172	147	125
0.8	a/W	0.855	0.812	0.812
	J _{Ic} , kJ/m ² (in-1b/in ²)	140.1 (800)	206.3 (1178)	215.9 (1231)
	dJ/da, MPa (1b/in ²)	274 (39,753)	168 (24,411)	134 (19,407)
	T	218	134	106

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COMPARISON OF COMPUTED AND MEASURED CRACK LENGTHS BASED ON THE EXPERIMENTAL COMPLIANCE EQUATION FOR THE LVDT RESULTS

-	% SG	0	0/ /0	10	1%	20)%
a/W		Meas	LVDT	Meas	LVDT	Meas	LVDT
	a	1.0530	1.0440	1.0387	1.0333	1.0290	1.0406
0.5	af	1.1603	1.1227	1.1437	1.1148	1.1150	1.1179
	a	0.1073	0.0787	0.1050	0.0815	0.0860	0.0773
	a	1.2301	1.2332	1.2384	1.2431	1.2461	1.2599
0.6	af	1.3244	1.3024	1.3281	1.3174	1.3280	1.3394
	a	0.0943	0.0692	0.0897	0.0743	0.0819	0.0795
	a	1.4464	1.4431	1.4468	1.4470	1.4391	1.4524
0.7	af	1.5467	1.5161	1.5291	1.5087	1.5083	1.5138
	a	0.1003	0.0730	0.0823	0.0617	0.0692	0.0614
	a	1.7096	1.7101	1.6249	1.6177	1.6232	1.6245
0.8	af	1.7676	1.7615	1.7063	1.6931	1.7013	1.7106
	a	0.0580	0.0514	0.0814	0.0754	0.0781	0.0861



CRACK EXTENSION, ∆a, mm

FIGURE 19. R-Curve for Specimen 02GAA1-47 (a/W = 0.5, % SG = 0) from the LVDT.



CRACK EXTENSION, Δa , mm

FIGURE 20. R-Curve for Specimen 02GAA1-34 (a/W = 0.5, % SG = 10) from the LVDT.



FIGURE 21. R-Curve for Specimen 02GAA1-36 (a/W = 0.5, % SG = 20) from the LVDT.



FIGURE 22. R-Curve for Specimen 02GAA1-143 (a/W = 0.6, % SG = 0) from the LVDT.



CRACK EXTENSION, ∆a, mm

FIGURE 23. R-Curve for Specimen 02GAA1-38 (a/W = 0.6, % SG = 10) from the LVDT.



FIGURE 24. R-Curve for Specimen 02GAA1-40 (a/W = 0.6, % SG = 20) from the LVDT.



FIGURE 25. R-Curve for Specimen 02GA603 (a/W = 0.7, % SG = 0) from the LVD1.



FIGURE 26. R-Curve for Specimen 02GAA1-41 (a/W = 0.7, % SG = 10) from the LVDT.



FIGURE 27. R-Curve for Specimen 02GAA1-43 (a/W = 0.7, % SG = 20) from the LVDT.



FIGURE 28. R-Curve for Specimen 02GAA1-28 (a/W = 0.8, % SG = 0) from the LVDT.



FIGURE 29. R-Curve for Specimen 02GAA1-45 (a/W = 0.8, % SG = 10) from the LVDT.



FIGURE 30. R-Curve for Specimen 02GAA1-46 (a/W = 0.8, % SG = 20) from the LVDT.

compliance equation, Equation (6), yields comparable results to the clip gage mounted at the load line on the crack plane and modeled by the Saxena-Hudak equation, Equation (3). Both systems measure initial compliance and compute initial crack length reasonably well; the respective compliance equations did not account for crack front tunneling. There are, however, some differences in the R-curves from the clip gage and LVDT extensometers. While they measure comparable initial crack lengths, the clip gage compliancebased crack length extension line often seems to indicate the onset of crack extension at a lower J value than that indicated by the LVDT compliancebased crack length extension line. This difference was largest where the a/W and % SG was the smallest (a/W = 0.5 and % SG = 0) and decreased as a/Wand % SG increased. The R-curves for specimens with high a/W and deeper side grooves (where constraint is greatest) show a negligible difference between extensometers. Work is currently in progress to resolve this matter.

The J-R curve results from both analyses indicate the shortcomings of the theoretical blunting line approximation, Equation (4), for use in unloading compliance J-R curves. For many specimens, the compliance-based apparent crack extension did not lie on the straight line defined by Equation (4). The reason is simply that Equation (4) yields a quantity which is a physical displacement at the crack tip due to local <u>plastic</u> deformation while the compliance equations, Equations (3) and (5), relate the <u>elastic</u> compliance with physical crack length. Alternatives for the blunting line described by Equation (4) will be studied in subsequent work.

C. RECOMMENDED FUTURE WORK

It is recommended that multiple-specimen heat tint R-curves be developed for a number of specimen dimensions contained in the present test matrix. In doing this, the directly measured crack extension characteristics can be correlated with the unloading compliance behavior of the two extensometers.

It is also desirable to develop an alternative to the theoretical blurting line, Equation (4), which actually fits the unloading compliance data during blunting. A linear regression line through these data points may serve quite well.

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