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ROOM TEMPERATURE CRACK GROWTH RATES AND -20° F
FRACTURE TOUGHNESS OF WELDED $1\frac{1}{4}$ INCH A-285 STEEL PLATE

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16. Abstract

Data are presented which were developed in support of a structural assessment of NASA-Lewis' 10-foot by 10-foot supersonic wind tunnel, critical portions of which are fabricated from rolled and welded $1\frac{1}{4}$ inch thick A-285 steel plate. Test material was flame cut from the tunnel wall and included longitudinal and circumferential weld joints. Parent metal, welds, and weld heat affected zone were tested. Tensile strength and fracture toughness were determined at -20° F, the estimated lowest tunnel operating temperature. Crack growth rates were measured at room temperature, where growth rates in service are expected to be highest.

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INTRODUCTION

The data presented in this paper were developed in support of a structural assessment of NASA-Lewis' 10-foot by 10-foot supersonic wind tunnel, critical portions of which are fabricated from rolled and welded carbon steel plate. An attempt was made to characterize the toughness of the plate (parent metal), welds, and weld heat affected zone at -20° F (estimated lowest operating temperature) in terms of the plane strain fracture toughness defined by ASTM Standard Method of Test E-399-74[1]. An additional -20° F tension test was made of a parent metal specimen containing a 3-inch long central through-crack. Conventional tensile properties of parent and weld metal were determined at -20° F. Crack growth rates for parent and weld metal were determined at room temperature, where growth rates in service are expected to be highest.

LIST OF SYMBOLS

a	crack length
a_o	original crack length
Δa	increment of crack extension
$\Delta a/\Delta N$	crack growth rate
B	thickness

LT ⎫
LS ⎬ crack-plane orientations as defined by ASTM Method
TS ⎬ E-399-74
TL ⎭

K   crack tip stress intensity factor

K_{Ic} plane strain fracture toughness as defined by ASTM
            Method E-399-74

K_Q provisional value of plane strain fracture toughness as de-
            fined in ASTM Method E-399-74

ΔK stress intensity range

N   cycles

ΔN increment of accumulated cycles

P_Q secant offset load as defined in ASTM Method E-399-74

P_{max} maximum load in plane strain fracture toughness test

R   ratio of minimum-to-maximum cyclic load

S   three-point bend specimen support roller span length

W   width

σ_{ys} yield strength

MATERIAL

Test material was flame cut from the tunnel wall and included
both longitudinal and circumferential weld joints. The plate was
$1\frac{1}{4}$ inch thick hot rolled A-285[2] firebox quality grade C steel con-
forming to ASTM Specification A-20[3] for pressure vessel steel
plates. Welds were hand made by the shielded metal arc process
using compatible weld filler.

PROCEDURE

With the exception of a tension test of a parent metal specimen containing a 3-inch long central through-crack, all testing was performed under NASA-Lewis contract by Materials Research Laboratory, Incorporated.[a] The center-crack test was performed at NASA-Lewis. Specimens were taken from the test material according to the layout in figure 1.

Fracture Toughness

Plane strain fracture toughness, K_{Ic}, tests were made at -20° F using the ASTM alternative three-point bend specimen[1] of W/B = 1 (fig. 2). Parent metal specimens were oriented in the LT, LS, TS, and TL directions. The plate rolling direction is parallel with the tunnel circumference. The four specimen orientations, therefore, place cracks normal to the circumferential and longitudinal tunnel loading directions, propagating in both plate width and thickness. These represent all principal tunnel crack orientation and propagation directions. Weld-specimen cracks were located at the weld centerline with propagation in either the thickness or length directions. Only longitudinal welds, which bear the tunnel hoop load, were evaluated. Weld heat affected zone specimen cracks propagated in the thickness direction only. For these tests at -20° F, each specimen (with attached thermocouples) was loosely wrapped with an insulating blanket, and the entire package cooled to approximately -25° F in a dry ice chamber. The package was removed from the chamber and installed in a bend test fixture. The arms of a crack mouth opening displacement gage were then inserted through an opening in the insulating blanket, and specimen load applied when the temperature slowly recovered to -20° F as indicated by thermocouples spanning the crack. Specimen temperature was virtually constant during test loading.

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[a]Materials Research Laboratory, One Science Road, Glenwood, Ill., 60425.

4

Conventional Tensile Properties

Conventional tensile properties were determined at -20° F using 0.505-inch diameter cylindrical specimens (ASTM Standard E-8-69)[4] with 2-inch gage length. The specimens were cooled to -20° F in the same manner as the three-point bend fracture toughness specimens. Yield strengths were determined by the drop-of-beam method.

Center-Cracked Specimen Strength

Tension testing of a centrally through-cracked parent metal specimen (fig. 3)[b] was done at -20° F in a cryostat normally used for liquid hydrogen testing. The specimen was cooled to -20° F with evaporating liquid nitrogen and maintained at test temperature for about 1 hour prior to test loading. The specimen was provided with surface-mounted knife edges attached with number three drive screws (into 1/8-in. deep holes) located 3/16 inch on each side and at mid-length of the central crack. A clip-in gage using an LVDT sensor was mounted in the knife edges to measure crack opening displacement during loading.

Crack Growth Rates

Constant-amplitude cyclic-load crack growth rates were determined at room temperature using the ASTM alternative compact specimen[1] of W/B = 4 (fig. 4). Parent-metal specimen cracks were LT oriented. Weld-metal specimen cracks were located at the weld centerline and propagated along the weld length. The chevron crack-starter notch for all crack-growth specimens was 0.1 W deep. Crack length measurements were recorded at frequent intervals from 0.3 W to 0.6 W, well within

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[b]Largest specimen obtainable from available stock.

the specimen stress intensity factor calibration range, so as to give a nearly uniform distribution of $\Delta a/\Delta N$ versus ΔK data points. Load was cycled sinusoidally at R of 0.5 and frequency 15 to 25 cps. Ambient relative humidity was 30 to 50 percent. Growth rates ($\Delta a/\Delta N$) were determined from the crack length versus elapsed cycles data ("a" versus N) by means of the secant method; i.e., calculating the slope of the straight line connecting two adjacent points on the "a" versus N curve. Since the computed $\Delta a/\Delta N$ is the average rate over the increment, the average crack length within that increment was used to calculate the corresponding ΔK. Throughout the course of crack growth, crack front straightness was within 5 percent as determined by the procedure for evaluating crack front curvature in ASTM Method E-399-74[1] based on the observed initial precrack and terminal fatigue crack fronts.

RESULTS

Conventional Tensile Properties

The conventional tensile properties at -20° F are given in table I. Weld strength, particularly the yield, is decidedly superior to parent metal strength, and ductility correspondingly inferior.

Fracture Toughness

The results of fracture toughness tests at -20° F are reported in table II. For the weld metal, crack-orientation designations refer to the rolling direction of the plate joined by the welds. Only tunnel longitudinal welds were tested.

None of the K_Q values given in table II qualify as valid K_{Ic} results according to ASTM Method E-399-74[1], failing either or both the specimen thickness requirement $B \geq 2.5(K_Q/\sigma_{ys})^2$, or

the test record requirement $P_{max}/P_Q \leq 1.1$. The LT weld metal specimens (numbers 5 and 6) were additionally nonconformant. Their fatigue cracks failed to develop a straight front, but instead lagged at specimen mid-thickness, mirroring the chevron starter. Average crack length determined according to ASTM Method E-399-74 was less than the crack starter notch surface length.

A typical test record is shown in figure 5 and attests to the high toughness of this alloy, requiring ever-increasing load for continuous crack extension. The fractures were flat but coarse, comprised of what appears to be a fine and uniform mix of tearing and cleaving. There were only slight indications of shear lips.

No attempt was made to determine the heat affected zone yield strength, and consequently no assessment of the adequacy of specimen thickness for this metal condition could be made. The point is moot, however, since P_{max}/P_Q ratios were the highest for this metal condition.

Center-Cracked Specimen Strength

The load versus crack opening displacement record of this specimen is reproduced in figure 6. Like the fracture toughness specimen test records, a gentle and continuous curvature follows a short linear segment. As expected, the fracture is like that of the toughness specimens, but without their small shear lip. The net fracture stress of 38 ksi slightly exceeded the yield strength.

Crack Growth Rates

Parent-metal crack growth rates are presented in figure 7. Only the LT orientation was examined, corresponding to a tunnel through-crack subjected to hoop loading. The results for duplicate specimens are shown separately. The linear portion of the curves ("regime of the power law") was fitted with a

least-squares best-fit line, for which the equation is given in the figure. The data from neither specimen are sufficient to define the complete sigmoidal crack growth relationship, but taken together they do. Specimen number 3 establishes the lower end and suggests a threshold stress intensity range for crack growth of about 14 ksi (in.)$^{1/2}$. [c] Specimen number 4 establishes the upper end and indicates crack instability at around $\Delta K = 45$ ksi (in.)$^{1/2}$ [$K_{max} = 90$ ksi (in.)$^{1/2}$]. At intermediate cyclic stress intensity ranges, the data overlap with remarkable agreement.

Crack growth results for weld metal are given in figure 8. Crack propagation was along the weld centerline, and, like the parent metal, two specimens were tested. A threshold stress intensity range of about 15 ksi (in.)$^{1/2}$ is indicated, and growth remains stable at least up to 45 ksi (in.)$^{1/2}$ [$K_{max} = 90$ ksi (in.)$^{1/2}$].

All crack growth rate data are combined in figure 9 which shows some variance in threshold indication, but is remarkably consistent in defining the linear portion of crack growth. These results are consistent with other steels of this type.

DISCUSSION

The tunnel material in all conditions (parent metal, welds, and weld heat affected zone) is quite tough at the tunnel's esti-mated lowest operating temperature (-20° F). The plane strain fracture toughness at this temperature is too high to be measured using the specimens here which were limited to 1-inch machined thickness, and the K_Q values obtained underestimate K_{Ic}.[5]

With the exception of the value for specimen number 8 (ta-ble II), parent metal K_Q values are remarkably uniform. One

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[c]More rigorous examinations of higher alloyed pressure ves-sel steels indicate cyclic-load crack growth stress intensity range thresholds as low as $\Delta K = 4$ ksi (in.)$^{1/2}$, and it is possible that lower values would be indicated here had lower growth rates been explored.

is tempted to conclude that the product is therefore isotropic; however, it has been shown previously at this laboratory[5] that conclusions regarding the plane strain fracture toughness based on the results from insufficiently thick specimens may not be valid. This subject is discussed at length in reference (6).

Based on the K_Q values, it is also tempting to conclude that the weld metal and heat affected zones are tougher than the parent plate. Again, however, the results from insufficiently thick specimens are open to question. However, the authors' experience with ductile materials has frequently shown a correlation between improved toughness and increased ratio of yield-to-ultimate strengths. It is noted, table I, that the yield-to-ultimate ratio for weld metal substantially exceeds that for parent metal, tending to confirm the suggestion of superior weld toughness.

The inability to measure valid plane strain fracture toughness, K_{Ic}, frustrated the primary purpose of the investigation, which was to furnish data for the evaluation of critical flaw sizes and stresses and useful tunnel life at the severest operating conditions. To compensate, the center-cracked specimen test was run to determine the load-carrying capability of the tunnel wall in the presence of a flaw larger than one that could possibly escape detection either by inspection or by loss of tunnel pressure. It was recognized that an assumed circular defect grown through the thickness under uniform tension as a circular crack would have a length on the surface of origin twice the plate thickness at emergence on the opposite surface. The largest specimen obtainable from the available stock provided a 3-inch central crack, one-third the test width. The crack length exceeded the length of a credible "leaker", and its relative length of 33 percent gave maximum test sensitivity[7]. The specimen failed above yield, essentially insensitive to the long crack.

The crack growth kinetics measured in this investigation are well defined and are apparently the same for base and weld metal,

except for threshold stress intensity range which may be lower for the base metal. The crack growth rate of one base metal specimen (number 4) appears to accelerate toward instability at a stress intensity range approaching 45 ksi (in.)$^{1/2}$ [K_{max} = 90 ksi (in.)$^{1/2}$].

CONCLUSIONS

The following conclusions are supported by the results:

1. The -20° F plane strain fracture toughness, K_{Ic}, of the hot rolled A-285 steel plate investigated is higher than measurable using 1-inch thick specimens.

2. Welds and weld heat affected zones appear no less tough, and possibly tougher than parent metal at -20° F.

3. The high -20° F toughness suggested by conclusion (1) above was confirmed by the above-yield failure strength of the centrally through-cracked tension specimen.

4. Weld yield strength is decidedly superior to parent metal yield strength at -20° F.

5. Room temperature constant-amplitude cyclic-load crack growth rates of parent and weld metal are the same within an exceedingly narrow range of scatter.

6. Crack growth threshold stress intensity range for weld metal is as high as that for parent metal.

REFERENCES

1. Standard Method of Test for Plane-Strain Fracture Toughness of Metallic Materials, Stand. E-399-74. Annual Book of ASTM Standards, Am. Soc. Test. Mater.

2. Standard Specification for Pressure Vessel Plates, Carbon Steel, Low- and Intermediate-Tensile Strength, Stand. A-285. Annual Book of ASTM Standards, Am. Soc. Test. Mater.

3. Standard Specification for General Requirements for Steel Plates for Pressure Vessels, Stand. A-20. Annual Book of ASTM Standards, Am. Soc. Test. Mater.

4. Standard Method of Tension Testing of Metallic Materials, Stand. E-8-69. Annual Book of ASTM Standards, Am. Soc. Test. Mater.

5. Jones, M. H.; and Brown, W. F., Jr.: The Influence of Crack Length and Thickness in Plane Strain Fracture Toughness Tests. Review of Developments in Plane Strain Fracture Toughness Testing, W. F. Brown, Jr., ed., ASTM STP 463, 1970, pp. 63-101.

6. Shannon, J. L., Jr.; and Brown, W. F., Jr.: Discussion to paper by J. E. Campbell entitled: Fracture Toughness of High Strength Alloys at Low Temperatures - A Review. Fatigue and Fracture Toughness - Cryogenic Behavior, ASTM STP 556, 1974, pp. 21-25.

7. Sachs, G.; et al.: Relations Between the Notch Tensile Strength of Cylindrical and Prismatic Specimens of Titanium Alloys and Heat-Treated Steels. Trans. ASME, J. Basic Eng., vol. 82, June 1960, pp. 401-410.

Table 1. -20°F Conventional Tensile Properties of Welded A-285 Steel Plate
Extracted From Wall of NASA-LeRC 10-foot x 10-foot Supersonic Wind Tunnel.

Specimen Number	Test Direction (Weld Type)	Ultimate Strength ksi	Yield Strength* ksi	Elongation (4D) percent	Red. of Area percent
		BASE METAL			
9	Longitudinal	70.1	37.0	38.0	59.0
10	Longitudinal	65.2	36.1	39.0	62.3
19	Transverse	65.1	38.3	28.0	49.7
20	Transverse	64.5	34.6	33.5	55.0
		WELD METAL			
11	Along Weld ₵ (Circumferential)	72.4	60.8	29.0	46.0
12	Along Weld ₵ (Longitudinal)	73.3	64.9	16.0	31.1

* Drop of beam.

Plate longitudinal direction parallel to tunnel circumference.
Tensile specimens: 0.505-in uniform diameter x 2-in gage length.

Table 2. -20°F Plane Strain Fracture Toughness of Welded A-285 Steel Plate Extracted From Wall of NASA-LeRC 10-foot x 10-foot Supersonic Wind Tunnel.

Specimen Number	Crack Plane Orientation	B in	W in	S in	a_o in	P_Q kip	P_{max} kip	K_Q ksi-in$^{1/2}$	σ_{ys} ksi	$2.5(\frac{K_Q}{\sigma_{ys}})^2$ in	$\frac{P_{max}}{P_Q}$
					BASE METAL						
7	LT	1.193	1.194	4.78	0.62	3.312	4.900	28.8	36.6	1.55	1.48
8	LT	1.193	1.194	4.78	0.62	4.400	4.750	38.2	36.6	2.72	1.08
15	LS	1.180	1.176	4.78	0.58	3.400	5.650	28.1	36.6	1.47	1.66
16	LS	1.179	1.176	4.78	0.58	3.420	5.750	28.3	36.6	1.49	1.68
17	TS	1.180	1.176	4.78	0.59	3.350	6.300	28.5	36.4	1.53	1.88
18	TS	1.179	1.176	4.78	0.57	3.350	5.420	27.1	36.4	1.39	1.62
21	TL	1.193	1.194	4.78	0.62	3.050	4.520	26.5	36.4	1.33	1.48
22	TL	1.193	1.193	4.78	0.61	3.300	4.900	29.6	36.4	1.65	1.36
					WELD METAL						
5	LT	1.160	1.168	4.00	0.46*	6.250	10.400	33.3	62.8	0.70	1.66
6	LT	1.144	1.143	4.00	0.48*	5.587	9.387	33.6	62.8	0.72	1.68
13	LS	1.144	1.144	4.00	0.58	5.875	7.375	45.7	62.8	1.32	1.26
14	LS	1.144	1.144	4.00	0.56	5.870	8.500	43.3	62.8	1.19	1.45
					WELD HAZ						
23	LS	1.144	1.143	4.00	0.56	5.420	9.700	40.0			1.79
24	LS	1.143	1.143	4.00	0.60	4.480	9.100	37.1			2.03

* Irregular crack front.

Column-heading symbols defined in ASTM Standard Method of Test E-399-74.

FIG. 1 SPECIMEN LAYOUT
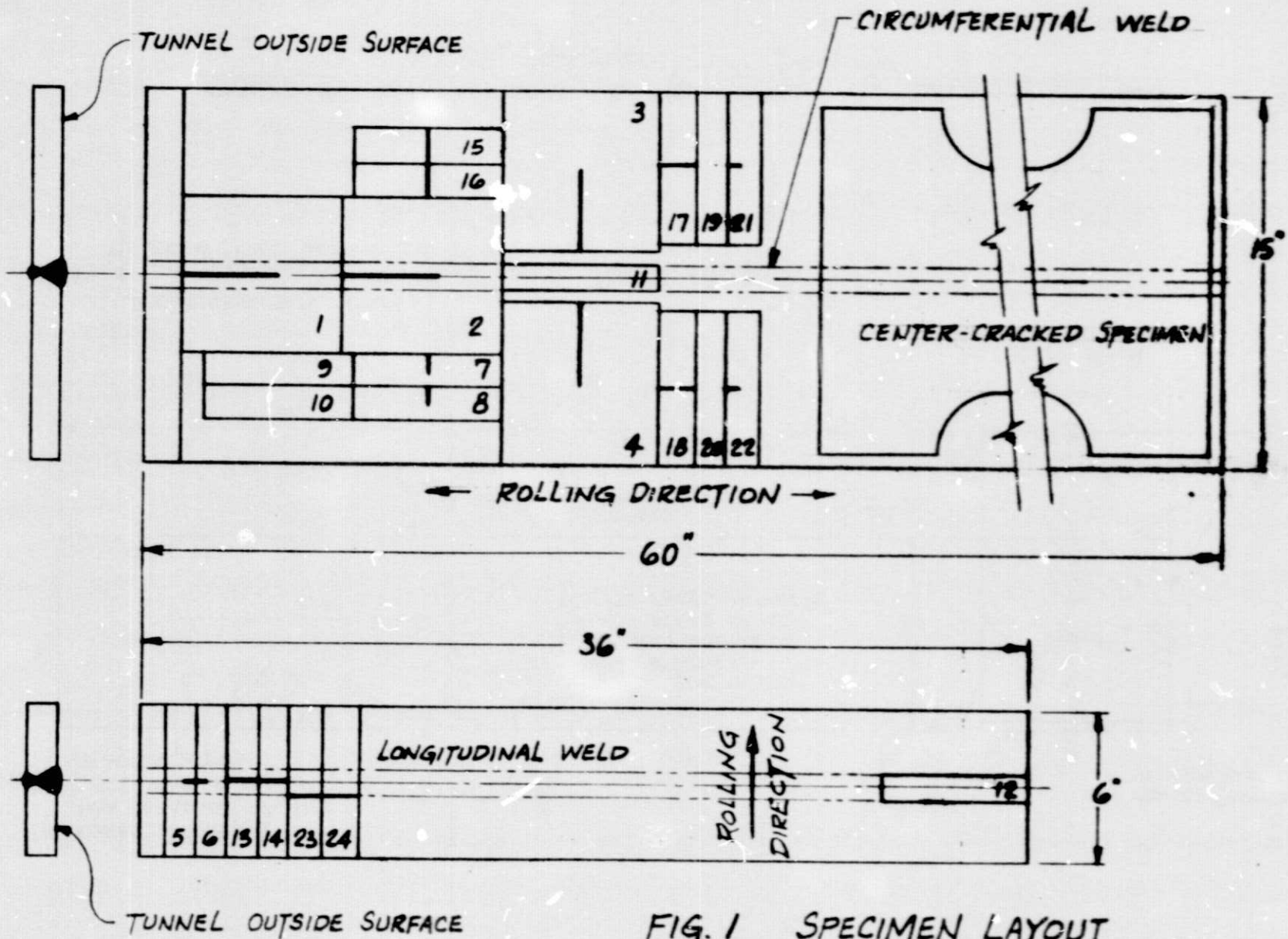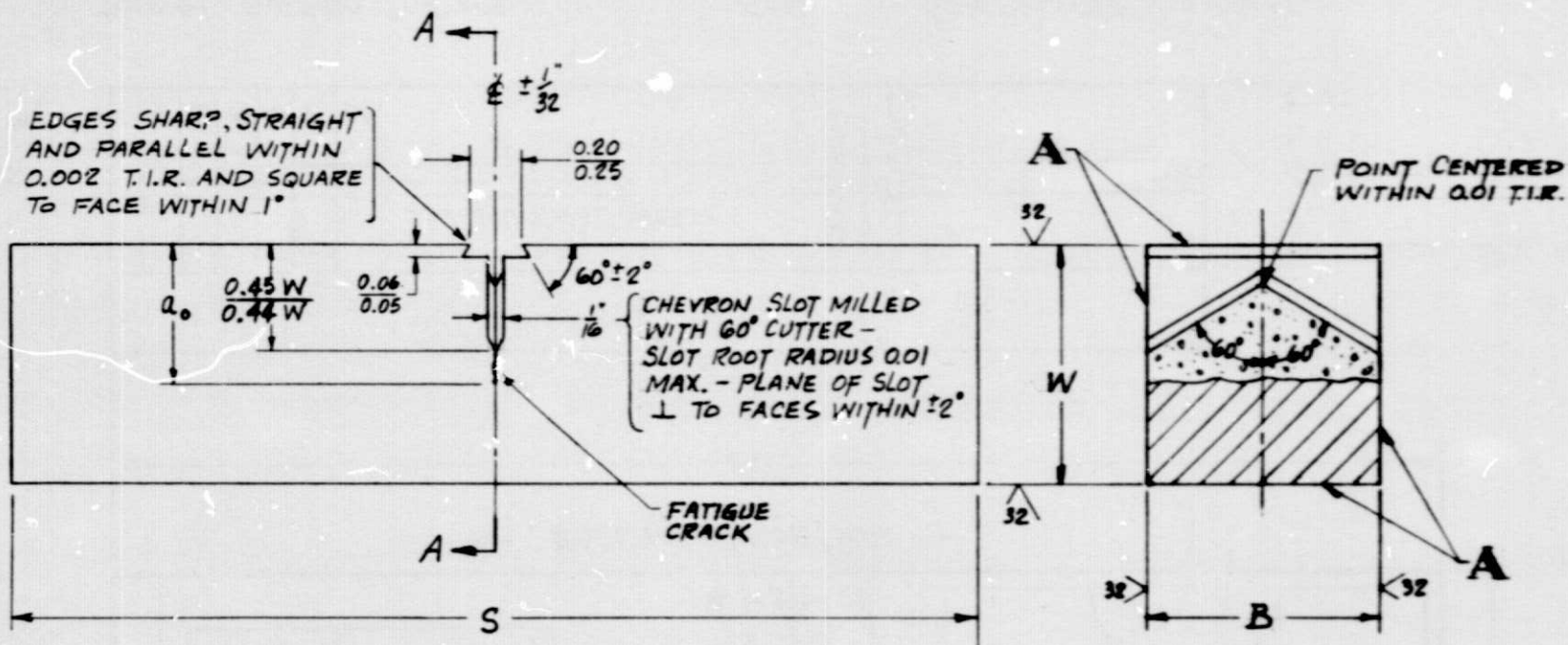
EDGES SHARP, STRAIGHT AND PARALLEL WITHIN 0.002 T.I.R. AND SQUARE TO FACE WITHIN 1°

$\underset{0.25}{0.20}$

$\mathbb{C} \pm \frac{1}{32}"$

$a_0 \quad \dfrac{0.45\,W}{0.44\,W}$

$\underset{0.05}{0.06}$

$60° \pm 2°$

$\frac{1}{16}"$

CHEVRON SLOT MILLED WITH 60° CUTTER — SLOT ROOT RADIUS 0.01 MAX. — PLANE OF SLOT ⊥ TO FACES WITHIN ±2°

FATIGUE CRACK

S

W

B

32

32

32

32

POINT CENTERED WITHIN 0.01 T.I.R.

60°   60°

SECT. A-A

NOTES:

1. ALL DIMENSIONS IN INCHES.

2. **A** SURFACES ARE PERPENDICULAR AND PARALLEL (AS APPLICABLE) TO EACH OTHER WITHIN .001 T.I.R.

FIGURE 2. ASTM ALTERNATIVE $\left(\frac{W}{B}=1\right)$ THREE-POINT BEND PLANE STRAIN FRACTURE TOUGHNESS TEST SPECIMEN

FIGURE 3. CENTRALLY THROUGH-CRACKED TENSION SPECIMEN
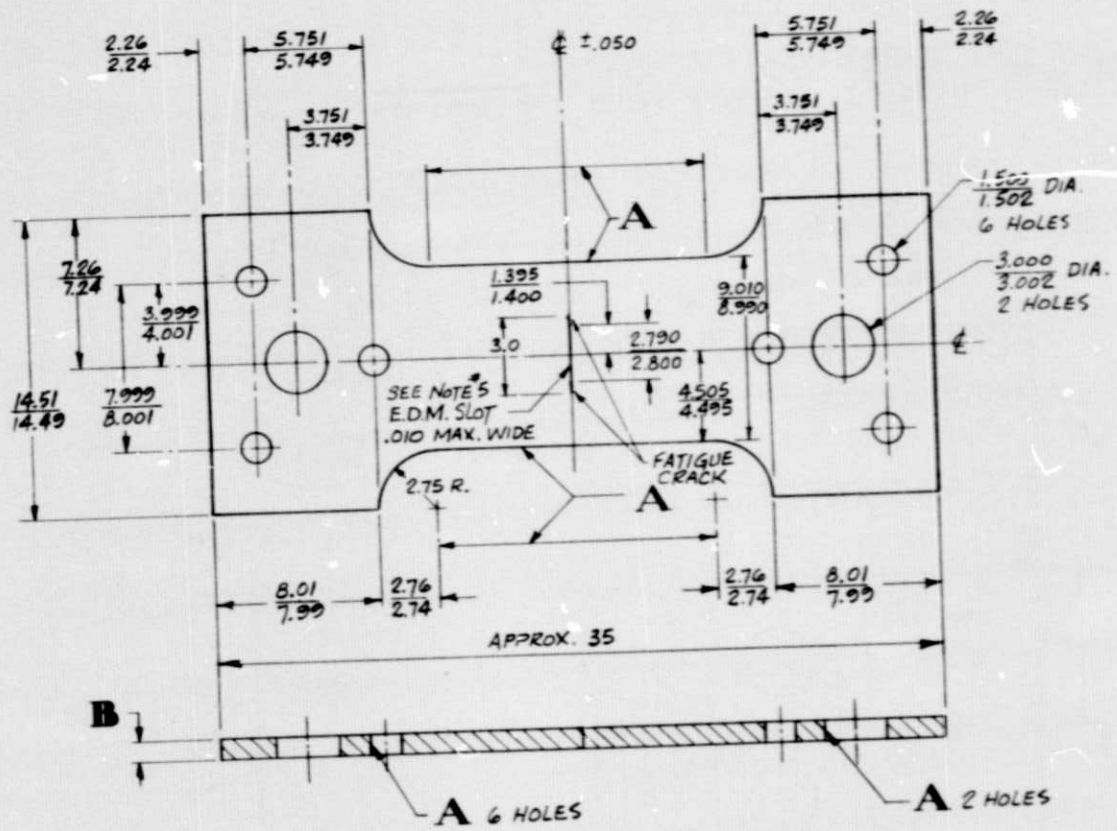
NOTES:
1. 64/ FINISH ALL OVER.

2. **A** SURFACES PARALLEL, FLAT, SQUARE & TRUE (AS APPLICABLE) TO EACH OTHER WITHIN .002 F.I.R.

3. **B** SURFACES PARALLEL, FLAT AND SQUARE TO **A** SURFACES WITHIN .005.

4. ALL DIMENSIONS IN INCHES

5. ELECTRIC DISCHARGE MACHINING DONE WITH MINIMUM HEAT DISTURBANCE TO SURROUNDING MATERIAL.
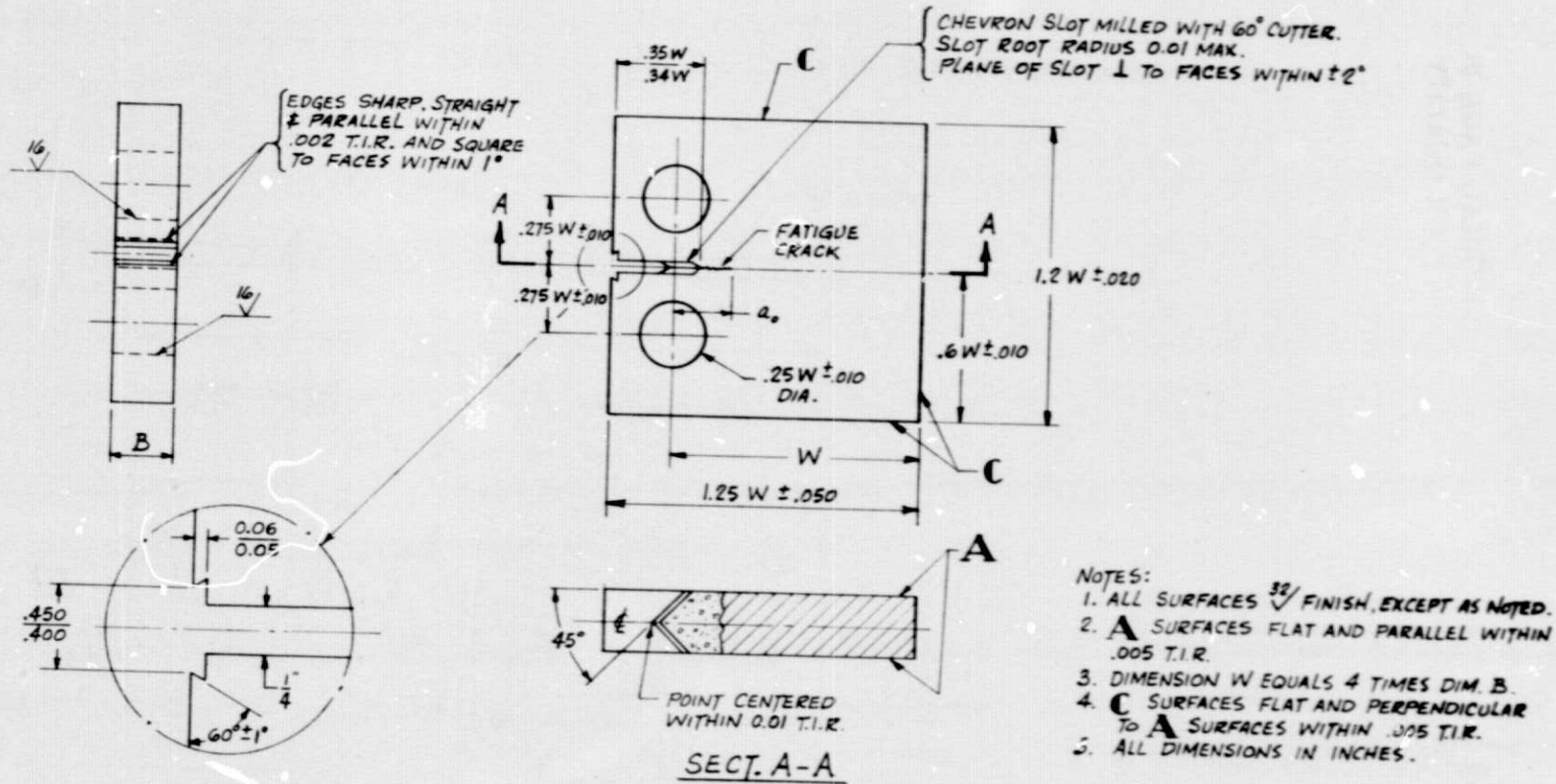
FIGURE 4. ASTM ALTERNATIVE $\left(W/B = 4\right)$ COMPACT SPECIMEN, USED IN CRACK-GROWTH RATE DETERMINATIONS
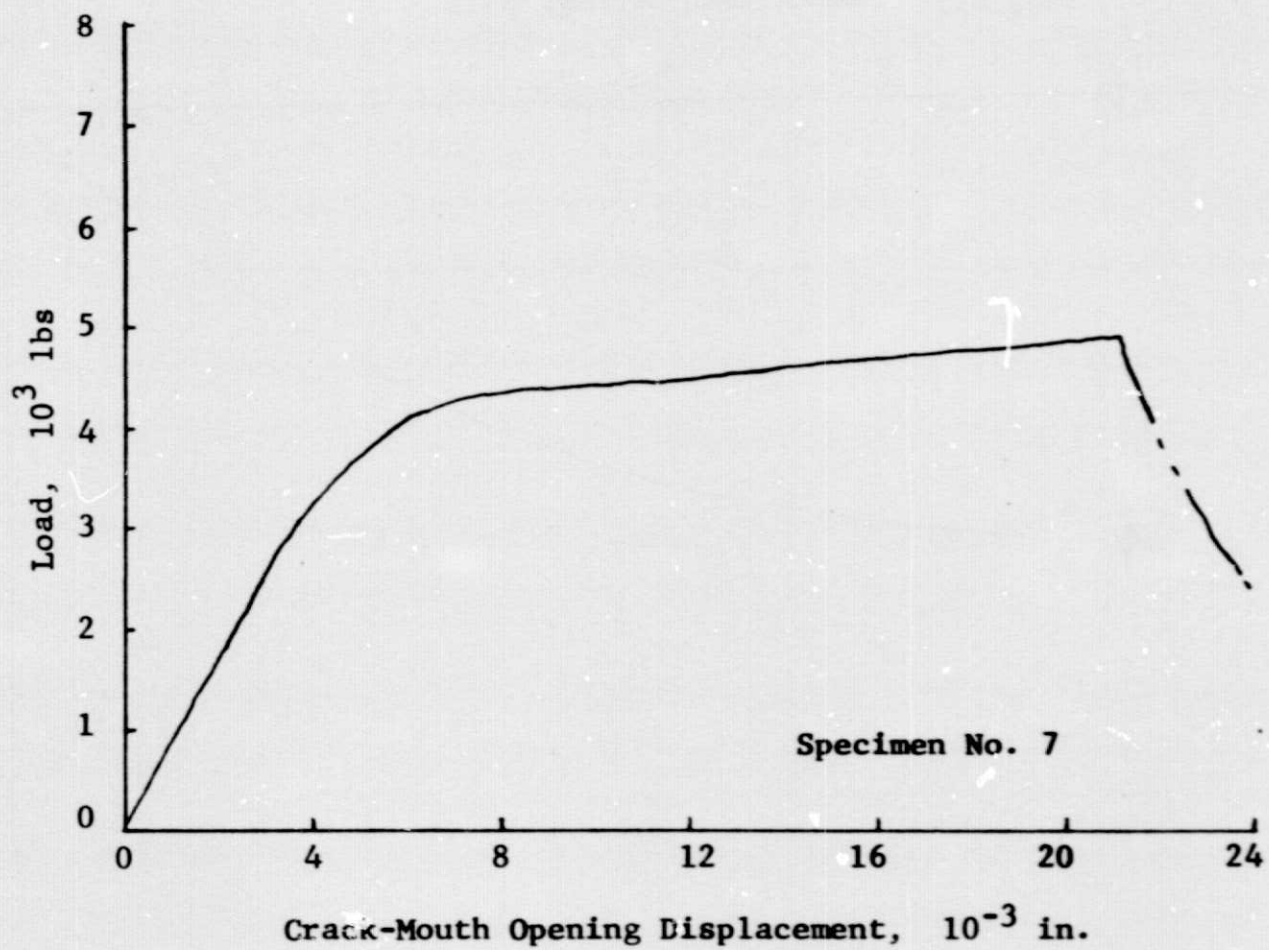
Figure 5. Typical load-displacement record from fracture toughness tests.
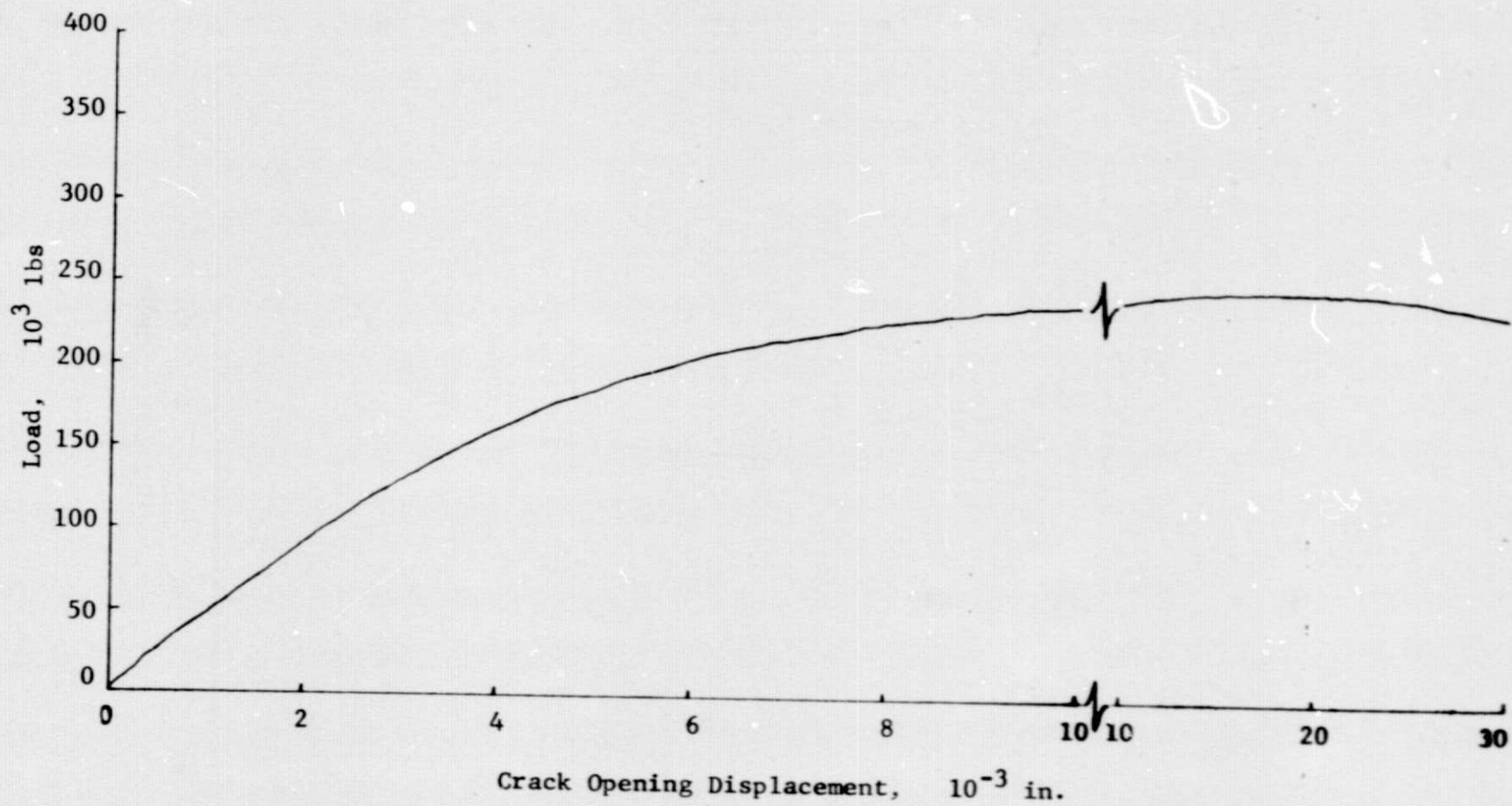
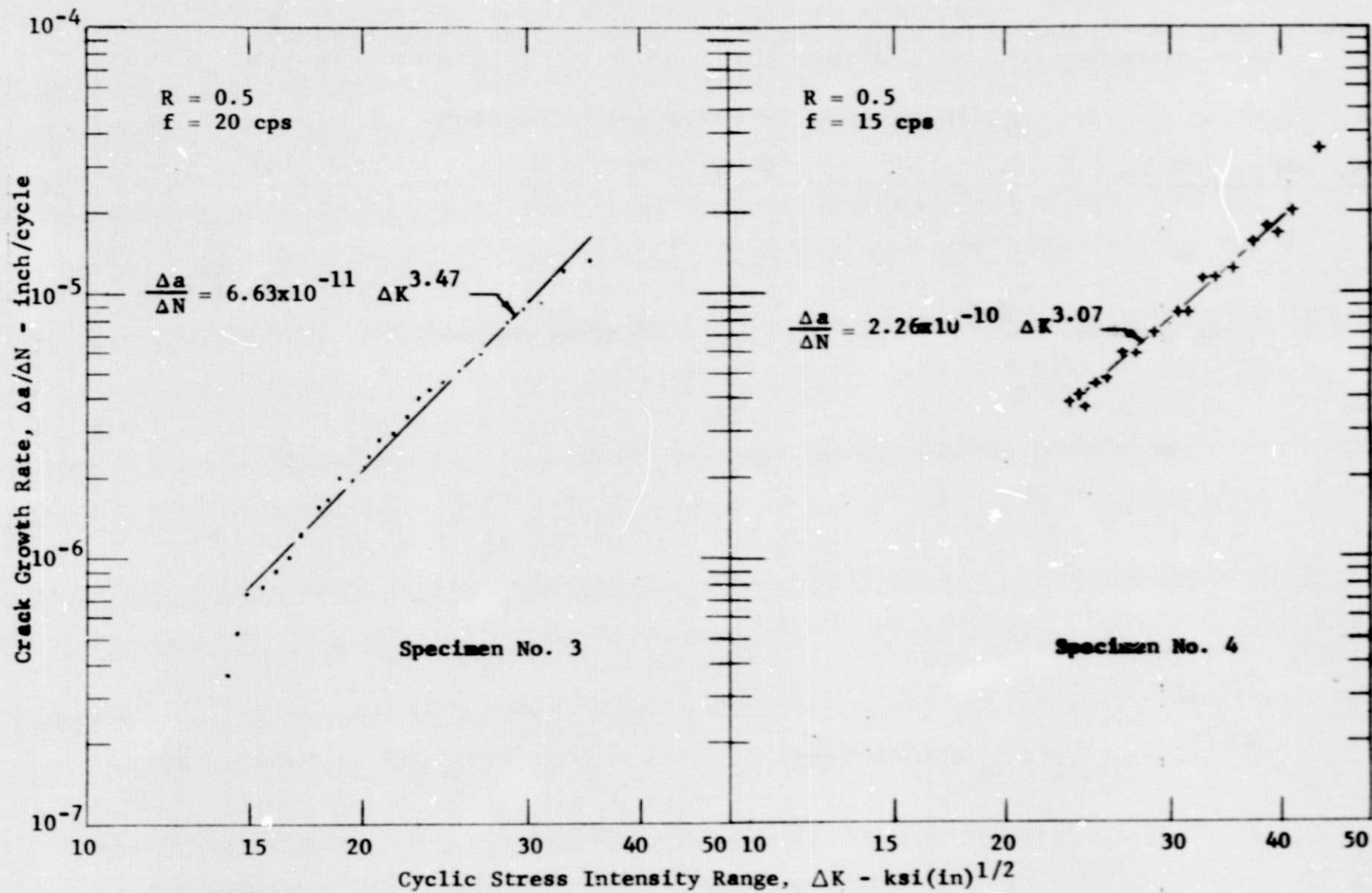Figure 6. Load-displacement record from centrally through-cracked specimen test.

Figure 7. Parent-metal crack growth rates (LT orientation) at room temperature under constant-amplitude cyclic loading for welded A-285 steel plate extracted from wall of NASA-LeRC 10-foot x 10-foot supersonic wind tunnel.
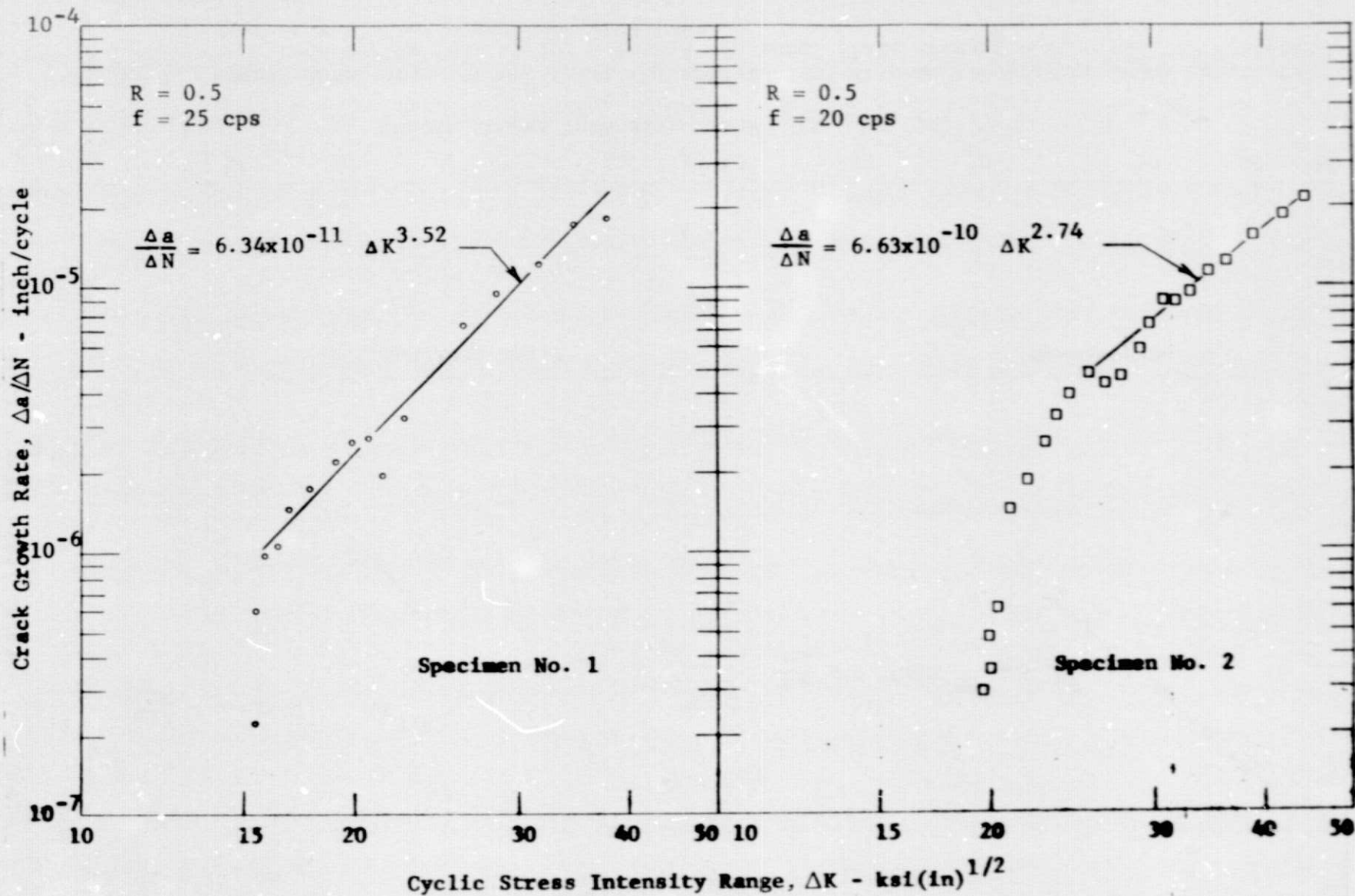
Figure 8.   Weld-metal crack growth rates (along weld centerline) at room temperature under constant-amplitude cyclic loading for welded A-285 steel plate extracted from wall of NASA-LeRC 10-foot x 10-foot supersonic wind tunnel.
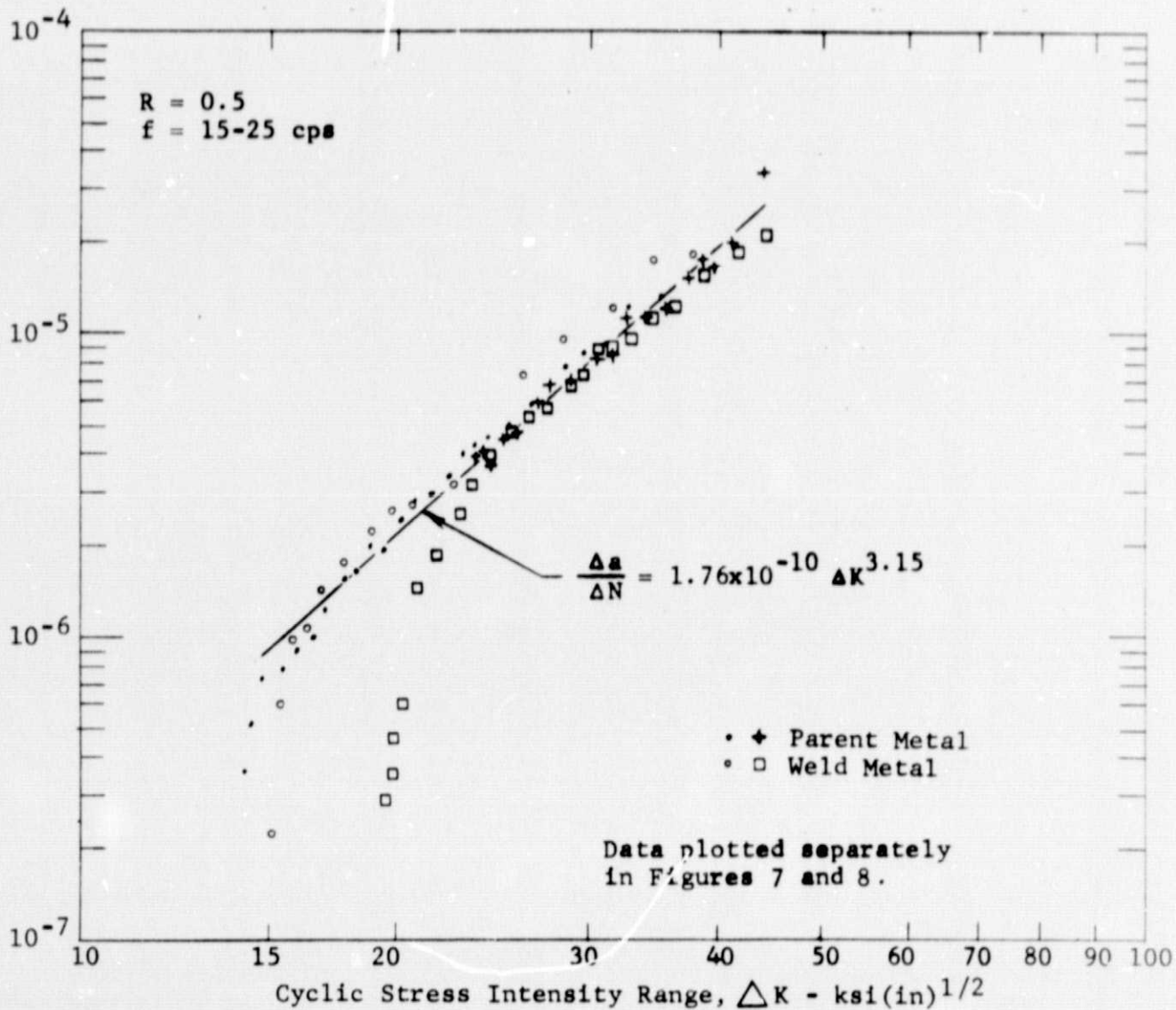
Figure 9. Parent-metal and weld-metal crack growth rates at room temperature under constant-amplitude cyclic loading for welded A-285 steel plate extracted from wall of NASA-LeRC 10-foot x 10-foot supersonic wind tunnel.