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CENTER NOTCH PLANE STRAIN K_{Ic} FRACTURE TOUGHNESS PROPERTIES OF SEVERAL HIGH-STRENGTH STEEL ALLOYS

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AIR FORCE SYSTEMS COMMAND
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FOREWORD

This report was prepared by Mr. Sidney O. Davis, Nathan G. Tupper, 1/Lt, USAF, and D. C. LaGrone, 1/Lt, USAF, Materials Information Branch, Materials Applications Division, Air Force Materials Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, and Roger M. Niemi of Monsanto Research Corporation, Dayton, Ohio. This program was conducted under Project No. 7381 "Materials Applications," Task No. 738106, "Design Information Development."

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The authors express their appreciation to Mr. Julius Teres, Air Force Materials Laboratory, for his support and assistance in designing the Acoustical Indicator Electronic Circuit.

This technical report has been reviewed and is approved.

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ABSTRACT

Plane strain fracture toughness and tensile properties were determined at room temperature, utilizing compliance and pop-in methods, for four high-strength steel alloys: PH 15-7 Mo, 17-7 PH, AM 350 and Vasco Jet 1000 (H-11). Fracture toughness values varied over a fairly wide range, with AM 350 having the highest at approximately 60.7 KSI $\sqrt{in.}$ and Vasco Jet 1000 (H-11) having the lowest at approximately 25 KSI $\sqrt{in.}$ A computer program used to reduce fracture toughness data was able to calculate critical crack length as well as fracture toughness when given either suitable compliance gage data or the measured test data. An acoustical pickup, used as an additional test monitor, is described. Analytical basis for the compliance method is presented.

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INTRODUCTION

As the quest for better performance aerospace systems continues, material strength requirements become higher and higher. The use of impact energy absorption test data has become inadequate for describing the toughness characteristics of materials. In the continuing search for high-strength material, it becomes more and more important to know (with accuracy) the behavior of a material (as a formed aerospace component) under service conditions. Therefore, a proposed material must be evaluated for its resistance to brittle fracture in the thicknesses, strength levels, and metallurgical conditions envisioned. If such an evaluation is not made, the behavior of the material is not completely characterized and either overdesign or underdesign can result. Both cases are undesirable -- overdesign will result in a heavy, inefficient structure, while underdesign can result in catastrophic failure.

The plane strain fracture toughness parameter, K_{Ic}, gives to the designer some measure of service performance when a small flaw is present in the material. By knowing the size of the largest flaw which can be tolerated in a structure, the designer can determine the stress level which will cause failure, and then design with an appropriate safety factor. Alternatively, he can determine the smallest flaw detectable with available inspection equipment, determine the stress level which will cause failure with this flaw present, and design below that stress.

Four high-strength steel alloys in sheet form were tested in this program. This report shows that the plane strain fracture toughness of high-strength alloys is very important even for relatively thin sheet.

MATERIALS

Table 1 shows a list of the four sheet materials, their thicknesses, and heat-treatment conditions used in this program. Standard heat-treatment designations were: PH 15-7 Mo, RH 950; 17-7 PH, RH 1050; AM 350, SCT 950; and Vasco Jet (VJ) 1000 (modified AISI type H-11), triple tempered at 1000°F. The alloy suppliers, heat numbers, and the chemical composition of the materials used in this program are also listed. Photomicrographs of the four sheet materials in the heat-treated condition are shown in Figure 1.

SPECIMENS

The fracture toughness tests conducted in this program used a 3 in. by 12 in. center notch specimen. A drawing of this specimen is shown in Figure 2.

The specimen preparation procedure was as follows: shear to size, drill 1 in. dia pinholes, heat-treat in fixtures, surface grind to remove scale, ‘‘Elox’’ center notch, drill shim holes, and tension-tension fatigue crack the starter notch to approximately 1 in. (1/3 W). The center notch was placed in the specimen after heat treatment to avoid any heat-treatment distortion problems. The specimens were heat-treated in an atmosphere of dissociated ammonia.

Recently, the ASTM committee on Fracture Testing of High-Strength Metallic Materials recommended that the specimen width-to-thickness ratio should be between 16 and 45. However, the specimens for this program were machined prior to this recommendation and the width-to-thickness ratios ranged from 50 for VJ 1000 to 85 for 17-7 PH. Because of the relatively thin sheet material used, considerable difficulty was experienced with buckling around the pinholes. To prevent this buckling, hardened steel carrier shims were used. These shims

TABLE 1. MATERIALS DATA

MATERIAL	THICKNESS (IN.)	ALLOY MANUFACTURER	CHEMICAL COMPOSITION	AS-RECEIVED CONDITION	AS-RECEIVED THICKNESS (IN.)	MIL SPEC NO.	HEAT TREATMENT	MANUFACTURERS' HEAT NUMBERS	HEAT-TREATMENT DESIGNATION
PH 15-7 Mo	0.050	ARMCO	Cr-15.32, Ni-7.11, Mo-2.39, Si-0.26, C-.09, Al-1.2 Mn-.55, Fe-bal	A	0.053	—	Soln: 1750° F-15 min Air Cool -100° F-8 hrs Age: 950° F-1 hr	—	RH 950
17-7 PH	0.036	ARMCO	Cr-17.18, Ni-7.16 Al-1.20, Mn-.66, Si-.23, C-.09, P-.018, S-.008	A	0.038	25043	Soln: 1750° F-15 min Air Cool -100° F-8 hrs Age: 1050° F-1 hr	T56038	RH 1050
AM 350	0.050	Alleghany Ludlum	Cr-16.42, Ni-4.3, Mo-2.88, Si-.27, C-.092, P-.016, S-.018, Co-.035, N-.10, Cu-.12 Al-.047, Fe-bal	H	0.052	AMS 5548	Soln: 1710° F-1 hr Air Cool -100° F-5 hrs Age: 950° F-3 hrs	89703	SCT 950
VASCO JET 1000	0.060	Vanadium Alloys	Cr-5.34, Mo-1.36, Si-.87, C-.39, Mn-.24, V-.48	—	0.062	—	Soln: 1850° F-1 hr Air Cool Age: 1000° F (2+2+2 hrs)	—	—

* A - Annealed
H - Heat treated

were fastened to the specimen by pins located in the three peripheral holes shown in Figure 2. These carrier shims, while not fastened to the grips, created more load bearing surface and distributed the stress around the pinholes. This method of shimming, as described in the first ASTM Fracture Toughness of High-Strength Steel Committee Report (Reference 1) offers a fast and convenient means to eliminate pinhole buckling problems.

Standard 2-in. gage length smooth tensile specimens were machined and heat-treated simultaneously with the fracture toughness specimens.

TEST EQUIPMENT

All tensile and fracture-toughness testing was done on a 50,000 lb Baldwin Universal tensile machine. The fracture specimens were fatigued-cracked in tension-tension using a 6-ton Schenck fatigue machine shown in Figure 3. Fatiguing at a maximum stress of 1/5 the yield stress at 2000 cycles/min produced fatigue cracks of the desired length in approximately 15 minutes. The brittle behavior of VJ 1000 necessitated a lowering of the maximum stress after crack initiation to prevent the fatigue crack from becoming unstable as it approached the desired length of 1 in. Fatigue crack lengths were measured after testing with a toolmaker's microscope.

The compliance gage chosen was originally developed by Richard W. Boyle at the Naval Research Laboratory (Reference 2). This compliance gage was modified to use a Model PS-6M Baldwin Microformer which provides a total magnification of approximately 550X. The compliance record was made on a Baldwin autographic recorder.

During the program it was found that the magnification produced by this combination of microformer and gage was insufficient to reliably record the pop-in event. It was then decided to obtain an acoustical indication of crack growth during the fracture test to help define the compliance pop-in (K_{Ic}) event. An uncalibrated acoustical indication was recorded on the Y axis simultaneously with load on the X axis of a Houston model HR-97 X-Y recorder. The load signal was obtained by attaching an auxiliary slide wire to the load indicator of the 50,000-lb tensile machine. The slide wire was one leg of a Wheatstone bridge measuring circuit. This gave an X axis record of the bridge unbalance as indicated by the position of the wiper arm on the slide wire. The bridge output was calibrated with the tensile machine load indication. An RCA magnetic cartridge (1940 vintage) with a 0.050 inch diameter wire pickup arm inserted in the notch gave an indication of crack activity. The acoustical signal was amplified with a Ballantine model 300 electronic voltmeter, filtered with a 20 KC high pass filter to eliminate machine noise, and rectified for the Y axis input. An additional monitor was obtained by using a high impedance Brush crystal head set in parallel to the X-Y recorder. A schematic of the acoustical monitoring circuit is shown in Figure 4.

Pictures of the test setup and a close-up of the compliance gage attached to the specimen are shown in Figures 5 and 6.

PROCEDURE

Wherever applicable, test procedures used were those recommended by the ASTM Committee on Fracture Testing of High-Strength Metallic Materials (References 3, 4 and 5).

After the specimens were fatigue-cracked, it was necessary to heat-tint the fatigue crack surface to make the starter crack visible for optical measurement. Heat-tinting was done at approximately 600°F for one hour.

The test data were obtained from the compliance gage recordings. The acoustical indications, previously described, were used to help determine the pop-in load when no distinct pop-in occurred on the compliance record. In some cases, the deviation from linearity of the compliance slope was used as a criteria for pop-in load determination. The lack of adequate elastic constraint in the sheet materials contributed to the failure to obtain distinct pop-in load values. The fracture-toughness value obtained by using the deviation from linearity is commonly designated by K_{nc} and has been used by other investigators when no clearly defined pop-in has occurred. In the tabulated data, a distinction has been made between K_{Ic} and K_{nc}. For some of the materials, the acoustical indications helped to interpret the data; however, the use of acoustical information has not been formally endorsed by the ASTM Committee.

A thin sheet center notch specimen has a predominate plane stress state rather than a plane strain state required for K_{Ic} conditions. For this reason the center notch fracture-toughness specimen is not considered an optimum specimen for reproducible K_{Ic} type measurements. Therefore, the K_{Ic} data presented in this report are primarily indicative only of the fracture initiation resistance properties of the materials.

Since it was impossible to prevent the compliance gage knife edges from moving during the latter stages of crack propagation, optical measurement of the critical crack length was not conducted. Instead, the sharp-notch strength has been used to indicate the fracture resistance of the material. The sharp-notch strength of a material is defined as the maximum load sustained before fracture divided by the nominal cross-sectional area, i.e.,

$$\frac{P_{max}}{B\,(W-2a_o)}$$

where P_{max} is the maximum load sustained, W is the width, B is the thickness and $2a_o$ is the original crack length.

COMPLIANCE GAGE CALIBRATION

To verify the compliance calibration curve reported by Richard W. Boyle (Reference 2), a gage calibration test for center notch specimens was conducted as a part of this program.

Nine 3 in. by 12 in. center-notch specimens of AM 350 were tested. Simulated cracks were prepared by hand sawing slot lengths ranging from 0 to 1.6 inches.

In this method of compliance gage calibration a plot of $Ev/\sigma W$ (ordinate) vs. $\pi a/W$ (abscissa) is used to calculate the crack length (2a) when the modulus of elasticity (E), specimen dimensions, and the deflections at all loads are known. Interested readers may refer to Mr. Boyle's discussion (Reference 2) for the mechanics of using the calibration curve.

Figure 7 compares our calibration curve with R. W. Boyle's curve. The excellent correspondence of curve shape is shown. The difference of ordinate ($Ev/\sigma W$) values is accounted for by the difference in Modulus of Elasticity of the materials used in the tests, i.e., steel versus aluminum, respectively.

The compliance gage calibration curve method for calculating the critical crack length (2a) of a material has been programmed as an optional part of the computer program which is discussed later.

The Irwin-Westergaard analytical basis for compliance measurements of fracture toughness is presented in Appendix II.

RESULTS AND DISCUSSION

Table 2 shows the base-line tensile test values which characterize the material used in the fracture-toughness tests. The yield strength value for PH 15-7 Mo is an estimated value obtained from existing literature. As discussed in Reference 1, an error of 10 percent in the yield stress will result in a 2 percent error in the fracture-toughness value when corrected for the plastic zone size.

A complete tabulation of the fracture data obtained for the four materials can be found in Tables 3, 4, 5 and 6. The initial stress intensity value of K has been tabulated as K_{nc} because the majority of K measurements were based on the deviation from linearity of the compliance gage record. Where a distinct pop-in occurred it is noted by an asterisk in the data tables.

All the materials tested had low notch strength to yield strength ratios. The following tabulation lists the fracture-toughness values obtained. Generally, the longitudinal specimen values were higher than the transverse values. A longitudinal specimen has its major axis parallel to the rolling direction of the material.

	K_{nc}		Notch Strength Ratio	
	Longitudinal	Transverse	Longitudinal	Transverse
PH 15-7 Mo	41.3	40.4	.241	.264
17-7 PH	52.6	50.3	.798	.658
AM 350	60.7	54.1	.972	.891
VJ 1000 (H-11)	25.3	25.0	.142	.135

Rockwell C hardness readings of the specimens tested showed consistent hardness values over the entire specimen. The Rc hardness ranges were: PH 15-7 Mo, 49.7 to 50.2; 17-7 PH, 42.5 to 43.8; AM 350, 44.5 to 45.5; VJ 1000, 58.2 to 59.5.

The fracture test values obtained were relatively consistent with the macroscopic fracture surface observations. A fracture surface with granular appearance corresponds to cleavage, or brittle fracture, while a fibrous appearance corresponds to a ductile failure.

	% Shear		Appearance of Fracture		
	Long.	Trans.	Longitudinal		Transverse
PH 15-7 Mo	5	5	Rough	and	Granular (G)
17-7 PH	85-90	30-40	Fibrous (F)	-	Mixed F & G
AM 350	95-100	40-50	Fibrous	-	Mixed F & G
VJ 1000	5	5	Smooth	and	Granular

The difficulties experienced in interpretation of some of the compliance curves have shown that a higher magnification than the 550X extensometer used in this program is desirable.

Jones and Brown (Reference 6) have recently reviewed the use of acoustical crack growth detection procedures and their value to the investigator. Their equipment has greater sensitivity and sophistication than the circuit described in Figure 4; however, some of their observations have been substantiated by this program. In particular, as the specimen thickness decreases, the signal-to-noise ratio decreases, thus permitting extraneous acoustical indications prior to a ''pop-in'' or a deviation from linearity. Extraneous noise is a problem especially with a screw driven test machine. The acoustical pickup serves to give the investigator an additional monitor during a test and may help to determine the ''pop-in'' load of the material.

The only comparative data values found in the literature were for VJ 1000 in Reference 4. A mean value of approximately 31 KSI $\sqrt{\text{in.}}$ for K_c found therein compares favorably with the K_{Ic} value of 25 KSI $\sqrt{\text{in.}}$ and the K_c values from 30 to 33 KSI $\sqrt{\text{in.}}$ obtained from the compliance records in this program.

CONCLUSIONS

1. This work has shown that of the alloys tested, VJ 1000 (H-11) has the lowest fracture toughness while AM 350 has the highest, although all values were lower than expected for the particular heat treatments tested.

2. The longitudinal and transverse fracture-toughness values were very similar, although the longitudinal values were slightly higher for the materials tested.

3. An acoustical monitor is of value in determining the pop-in load where a definite step pop-in criterion is used.

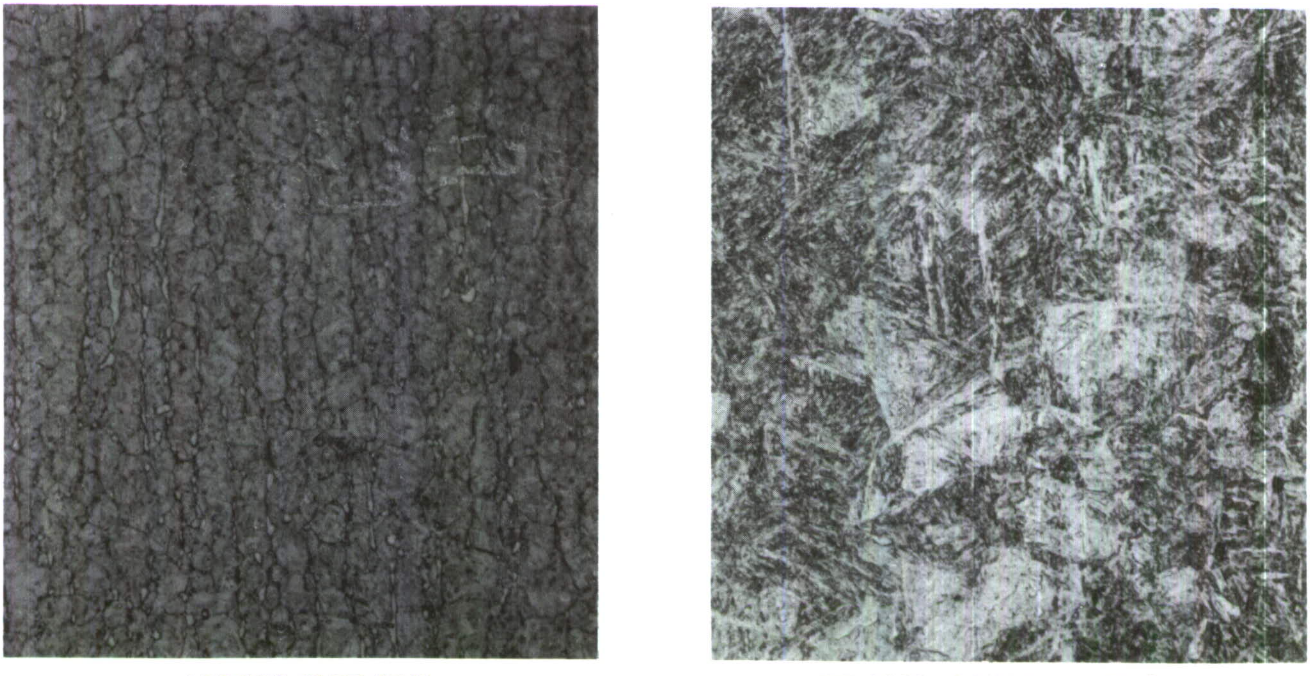
4. Fracture-toughness values obtained using the load at deviation from linearity of the compliance record did not differ appreciably from those obtained using a pop-in load.

5. A computer program greatly simplifies reduction of fracture-toughness data, especially when the compliance method is used.

6. The center-notched, fracture-toughness specimen is not a practical specimen for determination of plane strain fracture toughness. However, it is highly recommended as a plane stress specimen.

PH 15-7 Mo (RH 950)

17-7 PH (RH 1050)



AM 350 (SCT 950)

VJ 1000 (2+2+2 at 1000° F)

Figure 1. 500X Photomicrographs of Materials Tested. PH 15-7 Mo, 17-7 PH, AM 350 were etched with a solution of 5g $FeCl_3$, 50 ml HCl, and 100 ml H_2O, while VJ 1000 was etched with 4g $C_6H_2(NO_2)_3OH$ and 100 ml CH_3OH_1.

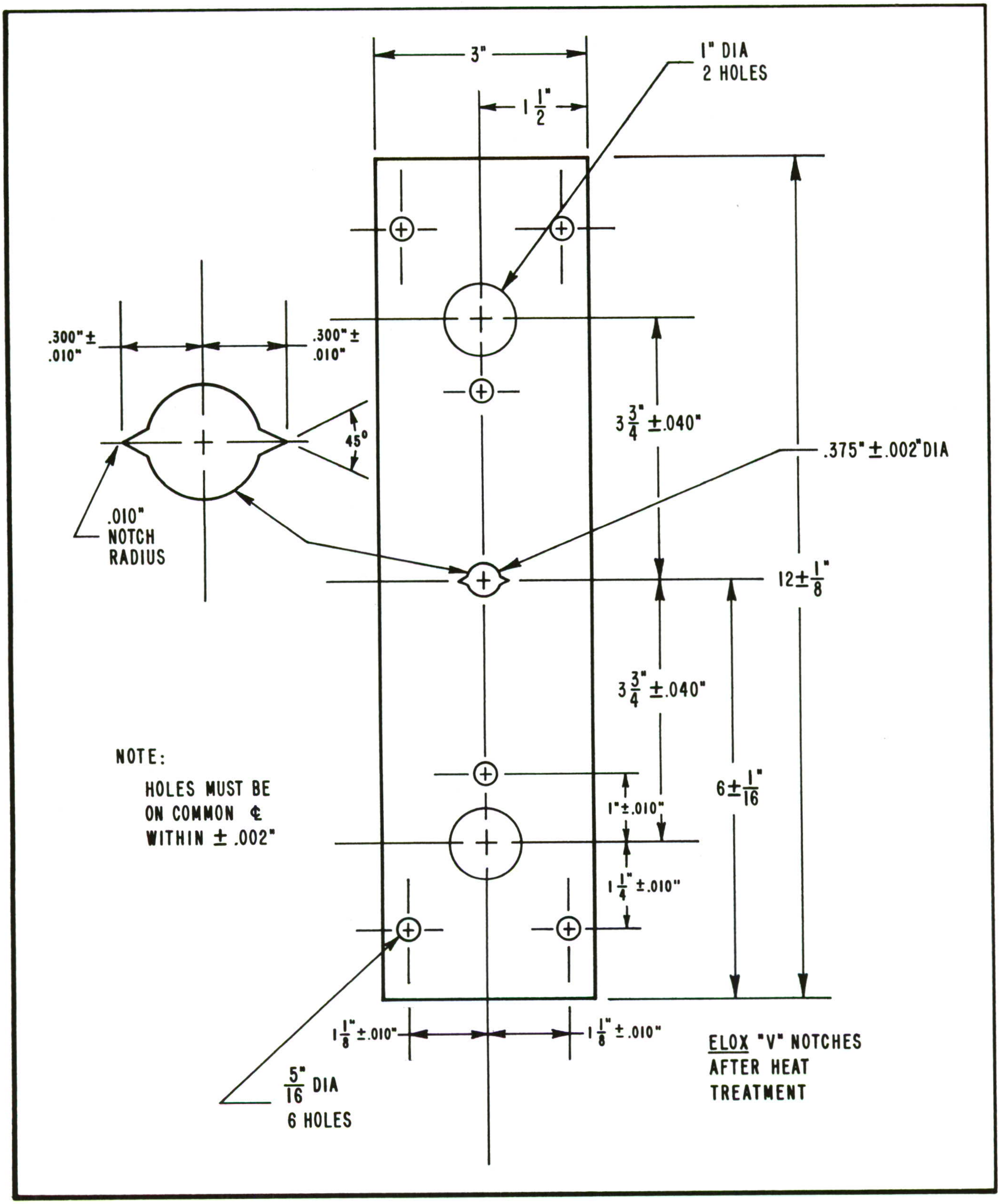


Figure 2. Center Notch Fracture Toughness Specimen

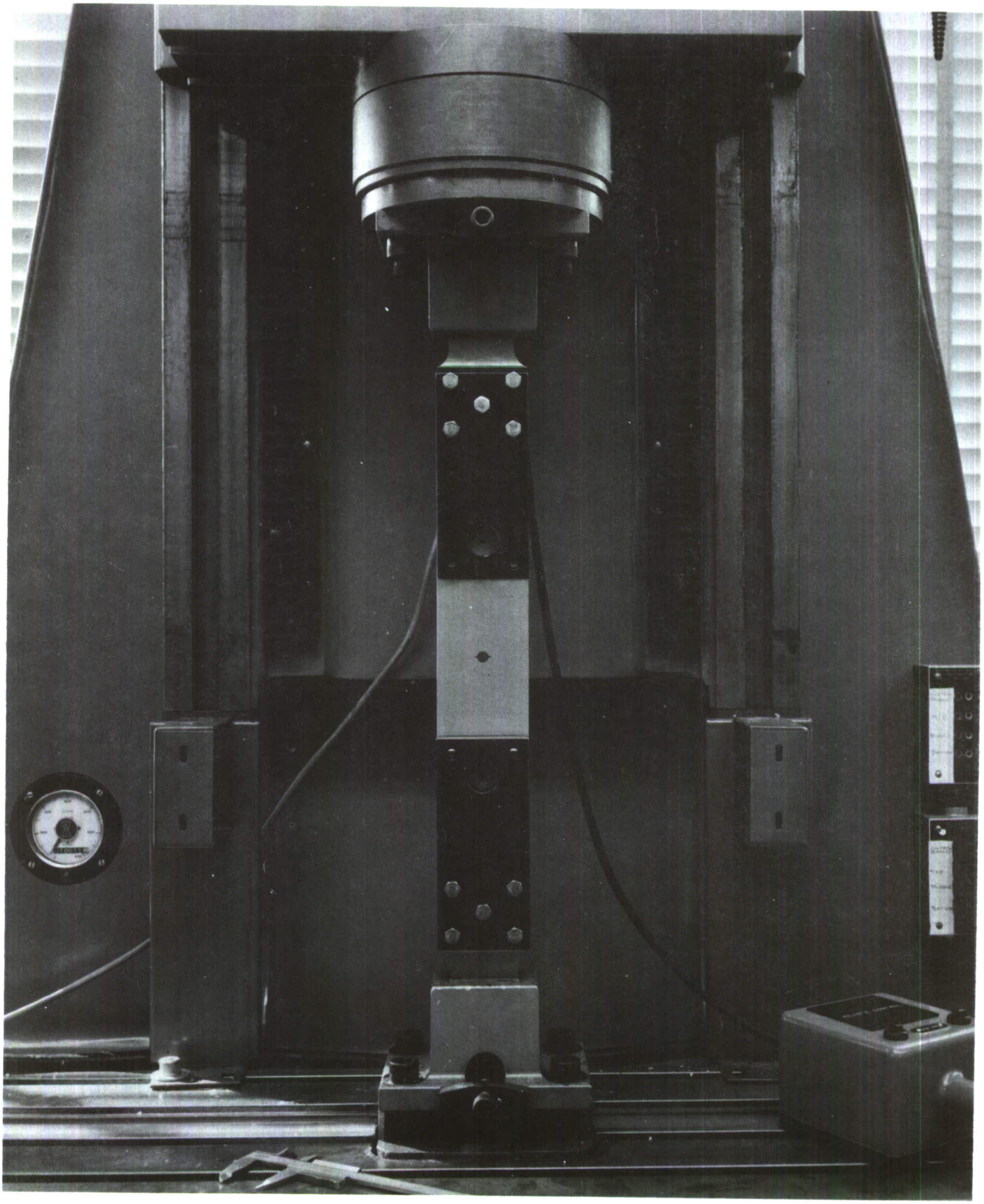


Figure 3. Fatigue Cracking Setup on a Six-Ton Schenck Fatigue Machine

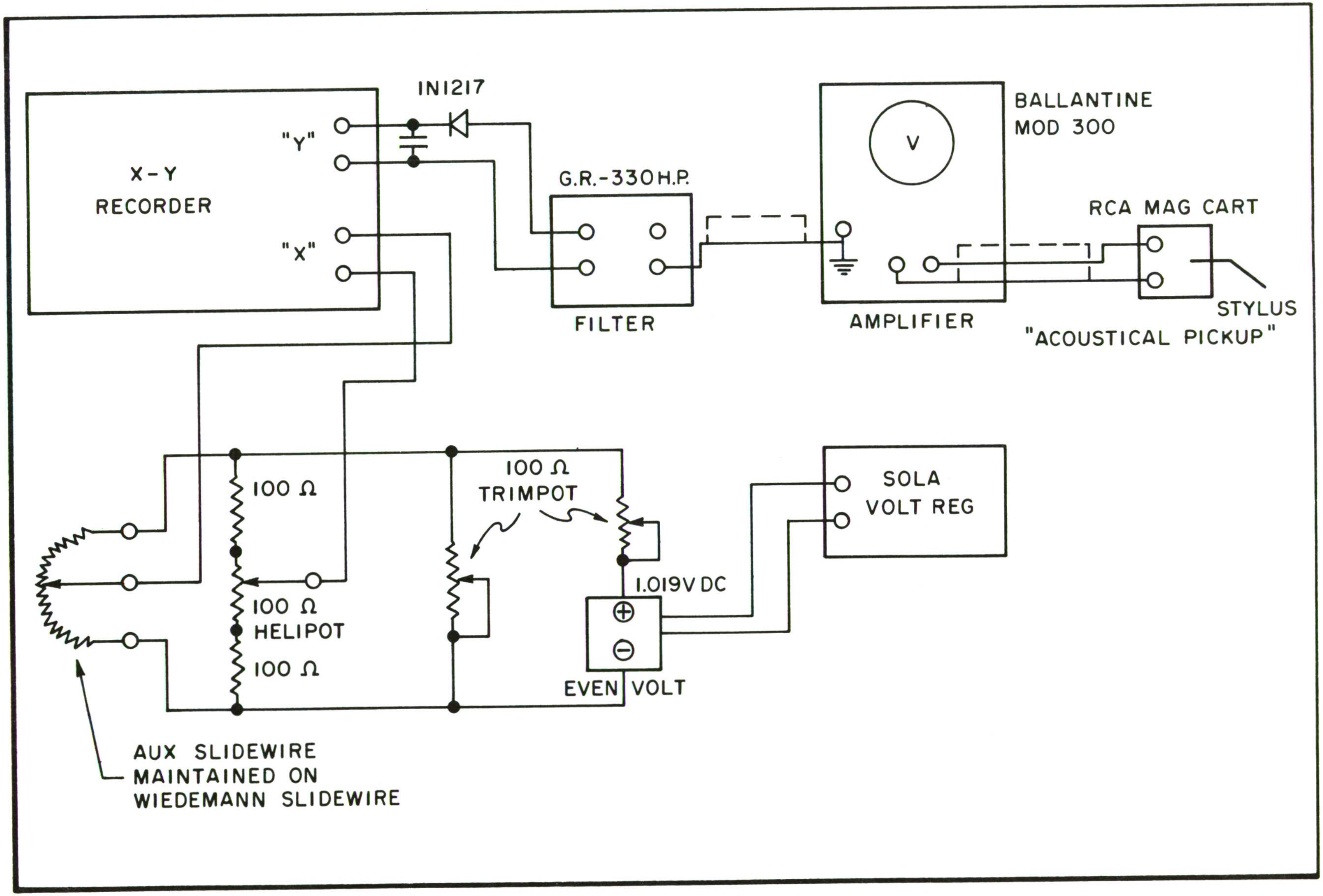


Figure 4. Schematic of Acoustical Indication Circuit

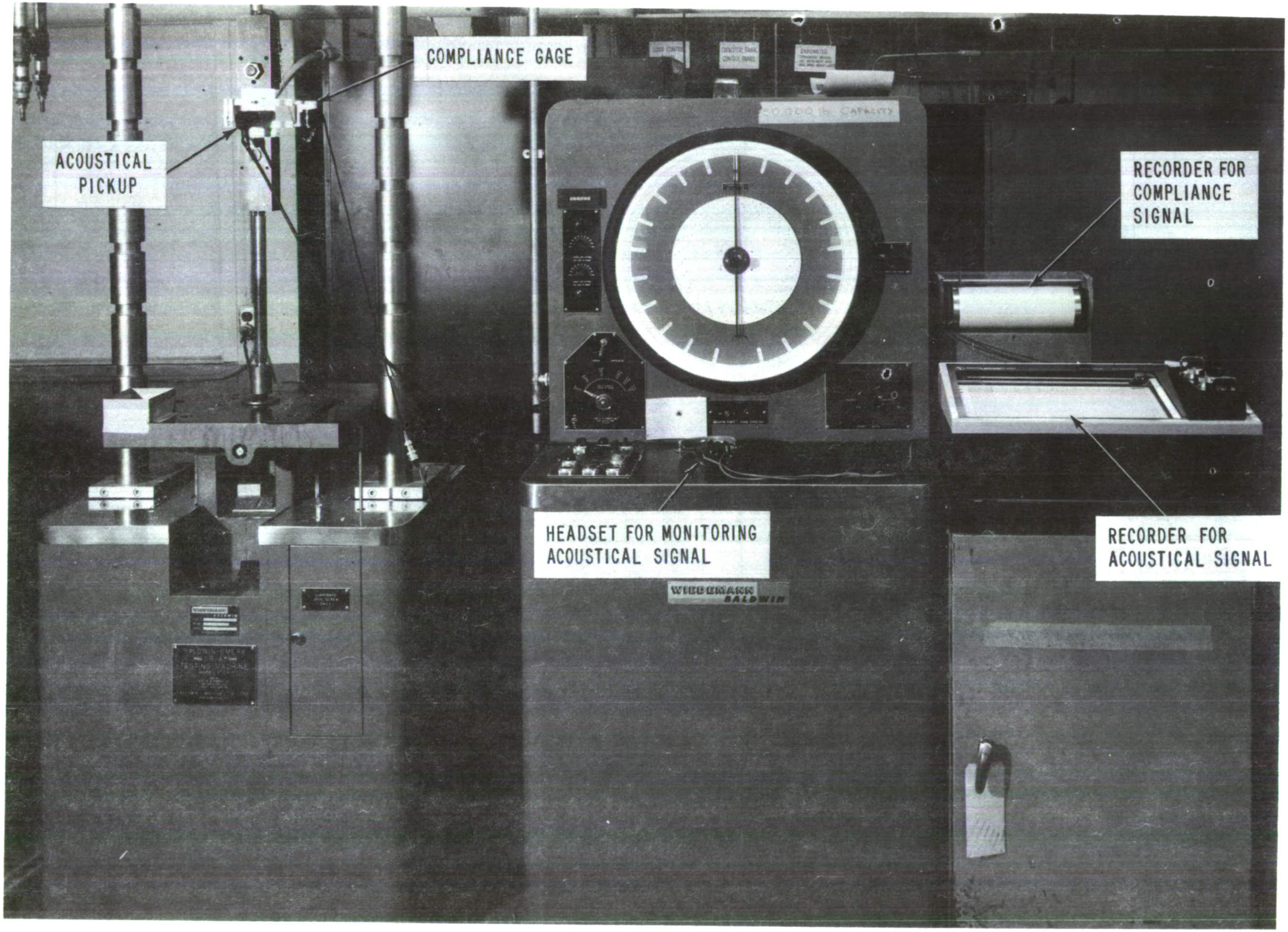


Figure 5. Test Equipment

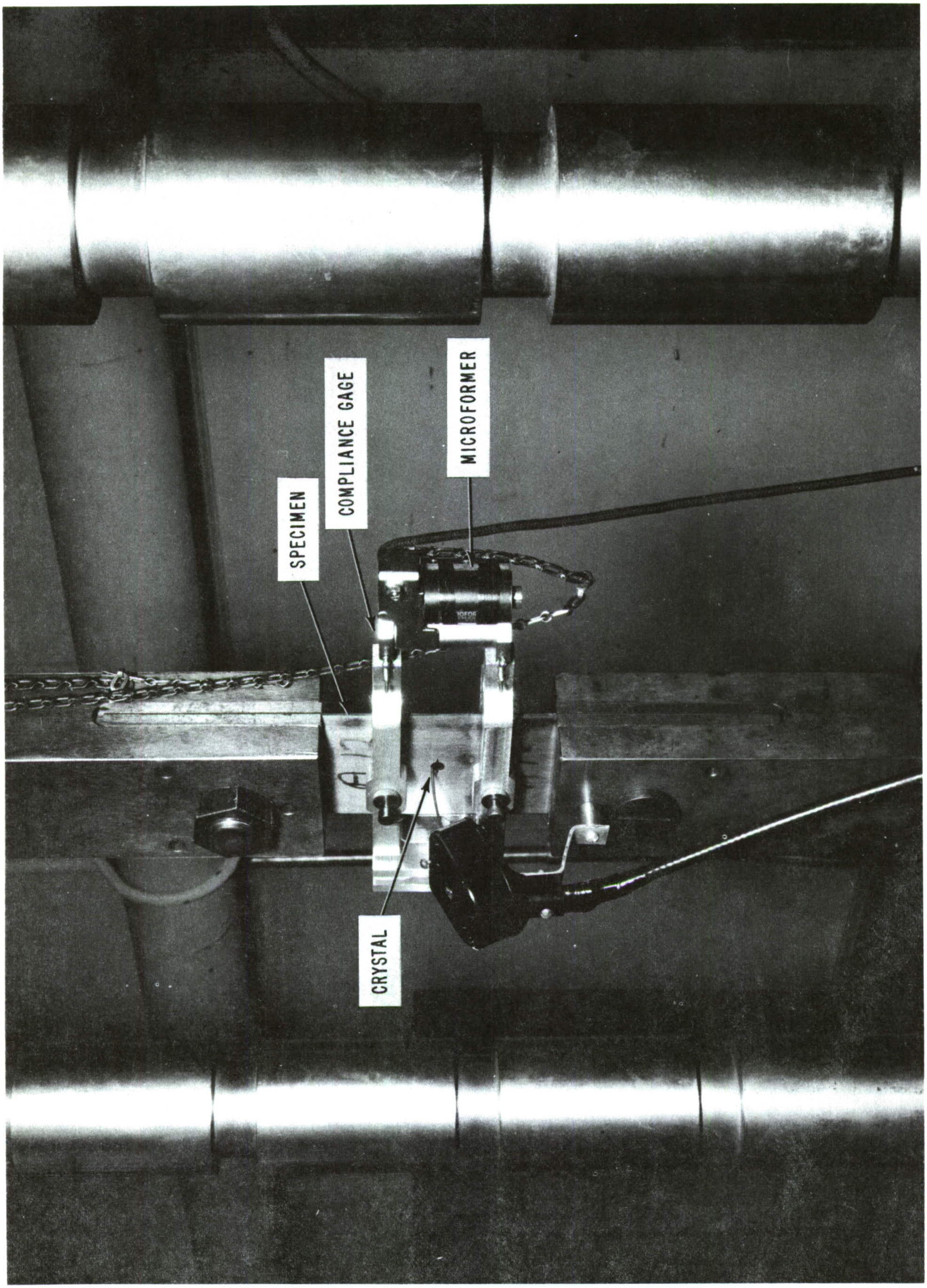


Figure 6. Close-up of Compliance Gage and Acoustical Pickup

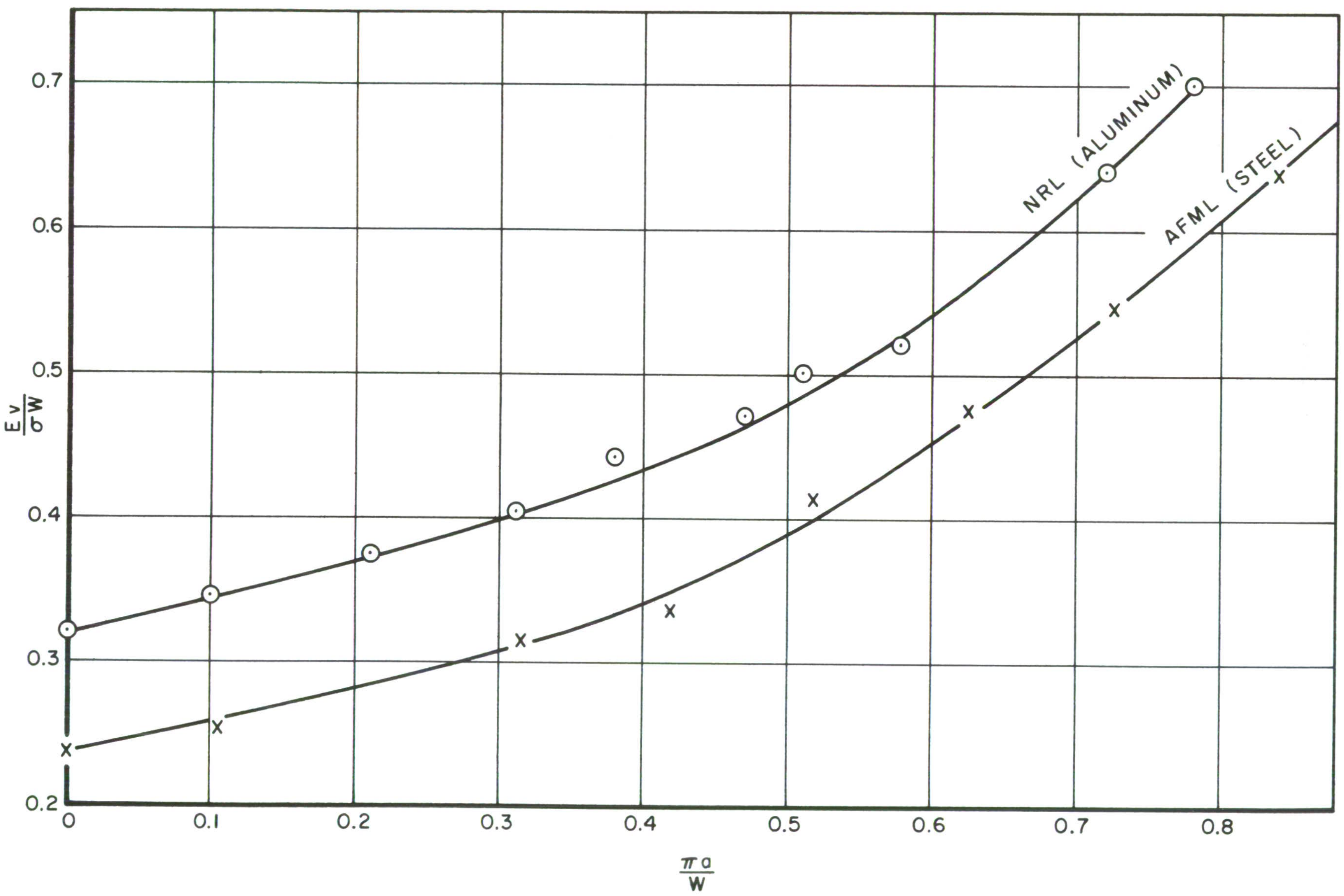


Figure 7. Comparison Compliance Gage Calibration Curves

TABLE 2. TENSILE TEST RESULTS

MATERIAL	SPECIMEN DIRECTION	.2% YIELD STRESS (KSI)	ULTIMATE STRESS (KSI)	% ELONGATION IN 2 IN.
17-7 PH	L	185.3	191.6	3.2
	L	188.0	194.8	4.0
	T	184.5	191.2	5.3
	T	186.3	190.4	5.0
AM 350	L	170.8	192.4	10.8
	L	169.4	194.1	10.5
	T	161.6	188.8	13.8
	T	165.0	189.0	13.8
VJ 1000 (H-11)	L	252.9	308.0	5.3
	L	248.4	301.3	5.2
	T	236.1	296.3	4.8
	T	234.7	297.5	4.8
PH 15-7 Mo*	L	220.0	240.0	8.0
	T	225.0	250.0	10.0

* Estimated Values from "Air Weapons Materials Application Handbook" (ARDC TR 59-66)

TABLE 3. FRACTURE TEST RESULTS FOR PH 15-7 Mo

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI $\sqrt{in}$)	DISTINCT POP-IN
L	3.02	.050	1.038	4.75 --	-- --	31.5 --	48.0 --	48.0 --	220.0	.22 --	-- --	.006	42.6 --	
L	3.02	.050	1.029	4.60 --	-- 5.33	30.5 35.3	46.3 53.6	46.3 --	220.0	.21 --	-- .24	.006	41.1 --	--
L	3.01	.050	1.017	4.45 --	-- 5.48	29.5 36.4	44.6 54.9	44.6 --	220.0	.20 --	-- .25	.005 --	39.5 --	--
L	3.01	.052	1.082	-- --	-- 4.97	-- 31.7	-- 49.5	-- --	220.0	-- --	-- .22	-- --	-- --	--
L	3.00	.0502	1.069	-- --	-- 5.02	-- 33.3	-- 51.7	-- --	220.0	-- --	-- .24	-- --	-- --	--
L	3.02	.0500	.921	-- --	-- 5.52	-- 36.6	-- 52.6	-- --	220.0	-- --	-- .24	-- --	-- --	--
L	3.00	.050	.976	4.70 --	-- 5.86	31.3 39.0	46.4 57.8	46.4 --	220.0	.21 --	-- .26	.005 --	40.9 --	--
L	3.02	.0503	1.040	4.74 --	-- 5.62	31.2 37.0	47.6 56.5	47.6 --	220.0	.22 --	-- .26	.006 --	42.4 --	†

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 3. FRACTURE TEST RESULTS FOR PH 15-7 Mo (cont.)

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI $\sqrt{in}$)	DISTINCT POP-IN
T	3.00	.0502	1.009	4.63 --	-- 6.66	30.7 44.1	46.2 66.5	46.2 --	225.0	.21 --	-- .30	.005 --	40.9 --	†
T	3.02	.0505	.994	4.55 --	-- 5.50	29.9 36.1	44.6 53.9	44.6 --	225.0	.20 --	-- .24	.005 --	39.4 --	†
T	3.01	.0505	1.034	-- --	-- 5.37	-- 35.3	-- 53.7	-- --	225.0	-- --	-- .24	-- --	-- --	--
T	3.01	.0505	.986	4.45 --	-- 5.83	29.3 38.4	43.6 57.2	43.6 --	225.0	.19 --	-- .25	.005 --	38.5 --	*
T	3.01	.0503	1.032	4.80 --	-- 6.10	31.7 40.3	48.2 61.2	48.2 --	225.0	.21 --	-- .27	.006 --	42.8 --	--
T	3.01	.0503	.963	4.75 --	-- 7.06	31.4 46.6	46.1 68.5	46.1 --	225.0	.20 --	-- .30	.005 --	40.6 --	--
T	3.01	.0502	1.005	-- --	-- 5.77	-- 38.1	-- 57.2	-- --	225.0	-- --	-- .25	-- --	-- --	--

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 4. FRACTURE TEST RESULTS FOR 17-7 PH

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI$\sqrt{in}$)	DISTINCT POP-IN
L	3.01	.0375	.980	4.50 --	-- 10.70	41.9 99.7	62.2 147.9	62.2 --	186.6	.33 --	-- .79	.014 --	55.4 --	--
L	2.99	.0358	.991	4.20 --	-- 10.38	39.2 96.8	58.6 144.6	58.6 --	186.6	.31 --	-- .78	.012 --	52.1 --	--
L	3.00	.0354	.992	4.00 --	-- 10.80	37.6 101.6	56.2 151.7	56.2 --	186.6	.30 --	-- .81	.011 --	50.0 --	--
L	3.02	.0358	.999	4.20 --	-- 11.10	38.9 102.8	58.1 153.6	58.1 --	186.6	.31 --	-- .82	.012 --	51.9 --	--
L	3.00	.0356	.973	4.35 --	-- 10.80	40.8 101.2	60.4 149.9	60.4 --	186.6	.32 --	-- .80	.013 --	53.6 --	--
L	3.00	.0360	1.005	-- --	-- 10.60	-- 98.2	-- 147.7	-- --	186.6	-- --	-- .79	-- --	-- --	-- †

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 4. FRACTURE TEST RESULTS FOR 17-7 PH (cont.)

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI $\sqrt{in}$)	DISTINCT POP-IN
T	2.99	.0353	1.008	3.40 --	-- 8.95	32.2 84.7	48.5 127.7	48.5 --	185.4	.26 --	-- .69	.009 --	43.0 --	--
T	3.00	.0352	1.031	4.23 --	-- 8.07	40.0 76.4	61.0 116.3	61.0 --	185.4	.33 --	-- .63	.014 --	54.6 --	--
T	3.00	.0352	.981	4.00 --	-- 8.62	37.9 81.7	56.4 121.5	56.4 --	185.4	.30 --	-- .66	.012 --	50.0 --	--
T	3.00	.0355	.988	3.95 --	-- 8.27	37.1 77.8	55.4 116.0	55.4 --	185.4	.30 --	-- .63	.011 --	49.2 --	†
T	3.00	.0348	.992	4.00 --	-- 8.63	38.3 82.6	57.1 123.2	57.1 --	185.4	.31 --	-- .66	.012 --	50.8 --	--
T	3.00	.0355	.981	3.90 --	-- 9.30	36.6 87.3	54.4 129.7	54.4 --	185.4	.29 --	-- .70	.011 --	48.3 --	--
T	3.00	.0354	.927	4.10 --	-- 8.90	38.6 83.8	55.9 121.4	55.9 --	185.4	.30 --	-- .65	.011 --	49.3 --	--
T	3.00	.0355	.920	4.20 --	-- 9.36	39.5 88.0	57.0 126.9	57.0 --	185.4	.31 --	-- .68	.012 --	50.2 --	

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 5. FRACTURE TEST RESULTS FOR AM 350

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO*	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI$\sqrt{in}$)	DISTINCT POP-IN
L	3.02	.0504	.995	6.88 --	-- 16.60	45.2 109.2	67.5 162.9	67.5 --	170.1	.40 --	-- .96	.020 --	60.8	--
L	3.01	.0490	1.003	6.72 --	-- 16.40	45.2 111.0	68.2 166.4	68.2 --	170.1	.40 --	-- .98	.021 --	61.5 --	--
L	3.01	.0502	.999	6.60 --	-- 16.65	43.6 110.0	65.2 164.6	65.2 --	170.1	.38 --	-- .97	.019 --	58.6 --	†
L	3.00	.0503	1.019	6.79 --	-- 16.35	44.9 108.2	68.0 163.7	68.0 --	170.1	.40 --	-- .96	.021 --	61.3 --	--
L	3.02	.0490	.956	6.92 --	-- 17.00	46.8 115.0	68.6 168.4	68.6 --	170.1	.40 --	-- .99	.021 --	61.5 --	--

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 5. FRACTURE TEST RESULTS FOR AM 350 (cont.)

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI $\sqrt{in}$)	DISTINCT POP-IN
T	3.02	.050	1.020	-- --	-- 13.90	-- 92.1	-- 139.1	-- --	163.3	-- --	-- .87	-- --	-- --	--
T	3.02	.0498	.989	6.25 --	-- 14.30	41.6 95.1	61.8 141.5	61.8 --	163.3	.38 --	-- .87	.018 --	55.5 --	--
T	3.02	.0500	1.009	6.00 --	-- 14.30	39.8 94.8	59.8 142.5	59.8 --	163.3	.37 --	-- .87	.017 --	53.7 --	--
T	3.01	.050	1.20	5.5 --	-- 13.80	36.5 91.7	60.7 152.4	60.7 --	163.3	.37 --	-- .93	.018 --	55.0 --	--
T	3.02	.0496	1.010	5.90 --	-- 14.10	39.4 94.1	59.2 141.5	59.2 --	163.3	.36 --	-- .87	.017 --	53.2 --	--
T	3.01	.0512	.989	6.25 --	-- 16.30	40.6 105.8	60.4 157.6	60.4 --	175.0	.35 --	-- .90	.015 --	54.0 --	†
T	3.00	.0505	1.125	5.75 --	-- 15.40	38.0 101.8	60.9 163.0	60.9 --	175.0	.35 --	-- .93	.016 --	54.8 --	†
T	3.00	.0515	1.206	5.40 --	-- 14.70	34.9 95.0	58.3 158.8	58.3 --	175.0	.33 --	-- .91	.014 --	52.5 --	†

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 6. FRACTURE TEST RESULTS FOR VASCO JET 1000

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI $\sqrt{in}$)	DISTINCT POP-IN
L	3.00	.0592	1.047	-- --	-- 4.00	-- 22.5	-- 34.5	-- --	250.6	-- --	-- .14	-- --	-- --	--
L	3.00	.0590	.961	3.45 --	-- 4.07	19.5 23.0	28.7 33.8	28.7 --	250.6	.11 --	-- .13	.002 --	25.1 --	--
L	3.00	.0595	.912	3.60 --	-- 4.38	20.1 24.5	28.9 35.2	28.9 --	250.6	.12 --	-- .14	.002 --	25.1 --	--
L	3.01	.0595	.896	3.60 --	-- 4.34	20.1 24.2	28.6 34.5	28.6 --	250.6	.11 --	-- .14	.002 --	24.8 --	--
L	3.01	.0591	.968	3.50 --	-- 4.56	19.7 25.7	29.0 37.8	29.0 --	250.6	.12 --	-- .15	.002 --	25.5 --	-- †
L	3.01	.0593	.996	3.55 --	-- 4.45	19.9 25.0	29.8 37.3	29.8 --	250.6	.12 --	-- .15	.002 --	26.2 --	--

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

TABLE 6. FRACTURE TEST RESULTS FOR VASCO JET 1000 (cont.)

DIRECTION	WIDTH (IN.)	THICKNESS (IN.)	INITIAL CRACK LENGTH (IN.)	P_{nc} LOAD (KIPS)	FRACTURE LOAD (KIPS)	GROSS STRESS (KSI)	NOMINAL STRESS (KSI)	NET STRESS (KSI)	YIELD STRESS (KSI)	NET RATIO *	NOTCH STRENGTH RATIO **	r_p (in)	K_{nc} (KSI$\sqrt{in}$)	DISTINCT POP-IN
T	3.01	.0612	.973	-- --	-- 3.70	-- 20.1	-- 29.7	-- --	235.4	-- --	-- .13	-- --	-- --	--
T	3.00	.0612	.976	3.30 --	-- 3.90	18.0 21.2	26.6 31.4	26.6 --	235.4	.11 --	-- .13	.002 --	23.3 --	--
T	3.00	.0611	.914	3.85 --	-- 4.64	21.0 25.3	30.2 36.4	30.2 --	235.4	.13 --	-- .15	.002 --	26.3 --	--
T	3.00	.0612	.923	3.50 --	-- 3.93	19.0 21.4	27.5 30.9	27.5 --	235.4	.12 --	-- .13	.002 --	23.9 --	--
T	3.00	.0612	1.025	3.50 --	-- 3.82	19.1 20.8	29.0 31.6	29.0 --	235.4	.12 --	-- .13	.002 --	25.5 --	†
T	3.00	.0611	.995	3.65 --	-- 4.15	19.9 22.6	29.8 33.8	29.8 --	235.4	.13 --	-- .14	.002 --	26.2 --	--

* 1 Net section stress at P_{nc}/yield stress

** 2 Nominal fracture stress/yield stress

† Indicates occurrence of a distinct pop-in

APPENDIX I

COMPUTER PROGRAM

DISCUSSION

The computer program, described below, was written to expedite the reduction of fracture toughness data. Two paths of calculation are available as distinguished by the value of a control variable JJ. When JJ is set equal to 1 (one) and suitable compliance gage data are supplied, the computer calculates the critical crack length of the material before calculating K_c and its associated parameters. If the critical crack length of the material is known, the compliance calculation will be bypassed by setting JJ equal to 2. The data input format for JJ=1 and 2 is discussed below.

This program has been written in IBM 7094 Fortran II language. To provide a simplified means of data input, closed subroutines VDECOM and DECDCP have been included. When using these subroutines, the input parameters for the source program can be sequentially placed on data cards in Columns 1 to 70. However, at least one space must be left between each entry and no single entry may overlap to the following data card.

The critical crack length calculation path (JJ=1) has been programmed using the Naval Research Laboratory's procedure. A fifth degree polynomial curve fit has been used to obtain the following equations:

$$\frac{Ev}{\sigma W} = f\left(\frac{\pi a}{W}\right) \quad \text{and} \quad \frac{\pi a}{W} = f\left(\frac{\sigma W}{Ev}\right)$$

These polynomial coefficients must be supplied as input data in the manner described below, regardless of the computation path desired. As written, the compliance calculation requires four sets of load-deflection values as input. The first three sets of values are read from the linear portion of the compliance curve. These values are averaged to obtain a representative value of $Ev/\sigma W$ which determines the magnitude of the calibration curve shift. The fourth set is the load-deflection values at fracture.

The basic fracture toughness calculations are made using Irwin's tangent equation

$$K^2 = \sigma_g^2 \, W \tan\left(\frac{\pi a_o}{W}\right)$$

The corrected K values incorporate the plastic zone correction factor where

$$a = a_o + r_p \quad \text{and} \quad K^2 = \sigma_g^2 \, W \tan\left(\frac{\pi a_o}{W} + \frac{K^2}{2W\sigma_{ys}^2}\right)$$

When the argument of the tangent function exceeds the mathematical limitations of Irwin's equation, no corrected K can be calculated, thus the same value as K basic is printed in the data output.

When all the input parameters necessary to make fracture toughness calculations are known (JJ=2), the source program will bypass the compliance calculation of the critical crack length.

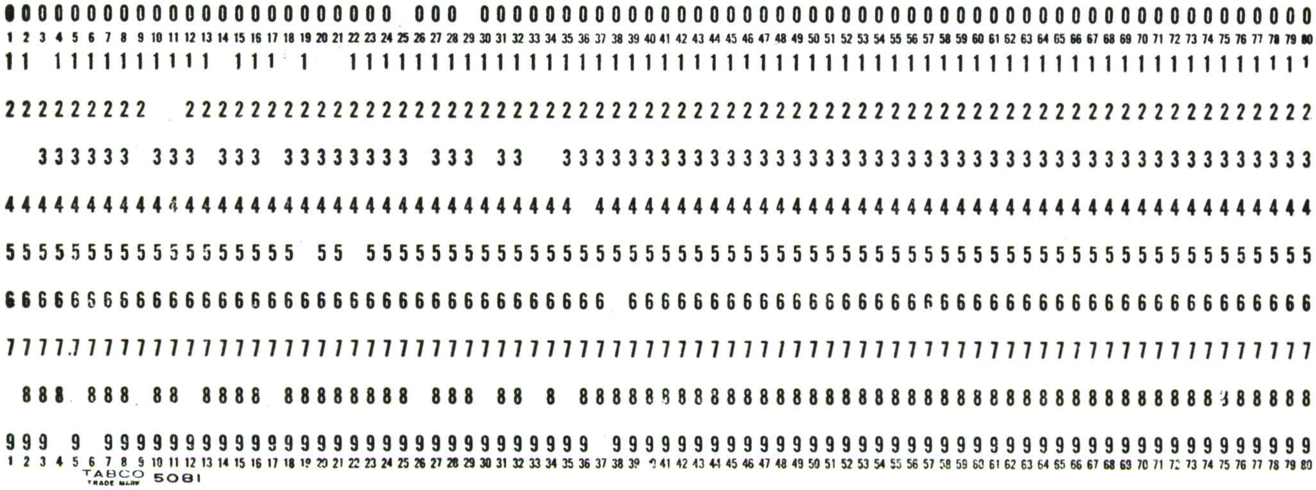
An example of the data output from this computer program is shown in Table 7.

DATA INPUT

All input data, except JJ, must be decimal values. The first two data cards for both JJ=1 and JJ=2 contain the polynominal curve fit constants shown below. The minimum one space format using columns 1 to 70 apply to all the data card input discussions. The constant data cards numbers 1 and 2 are supplied only once for all program runs.

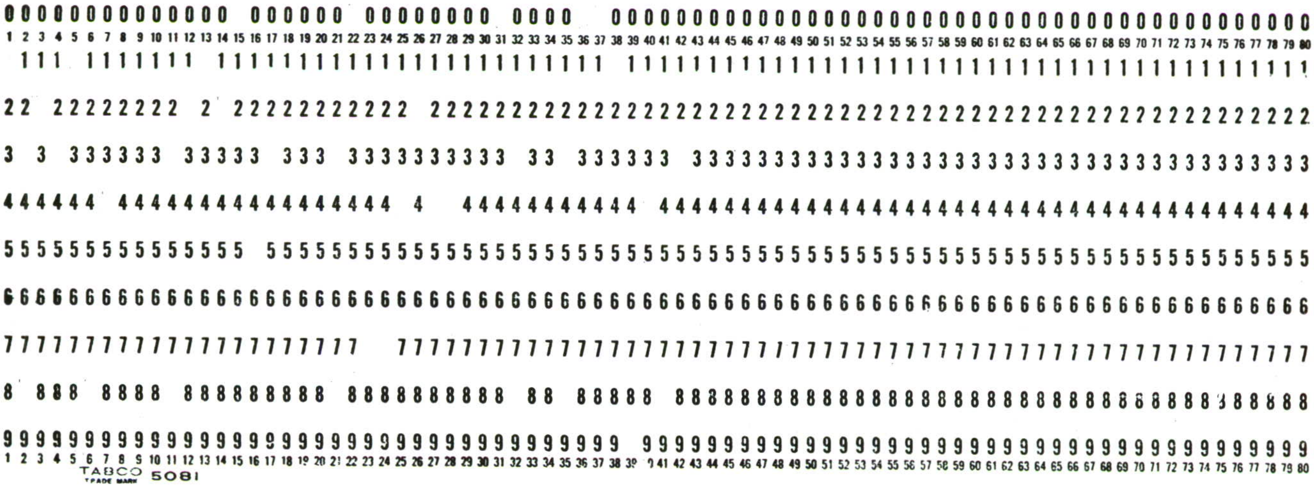
Card No. 1

```
.31989  .22831  .15115  0.  0.  .38496
```



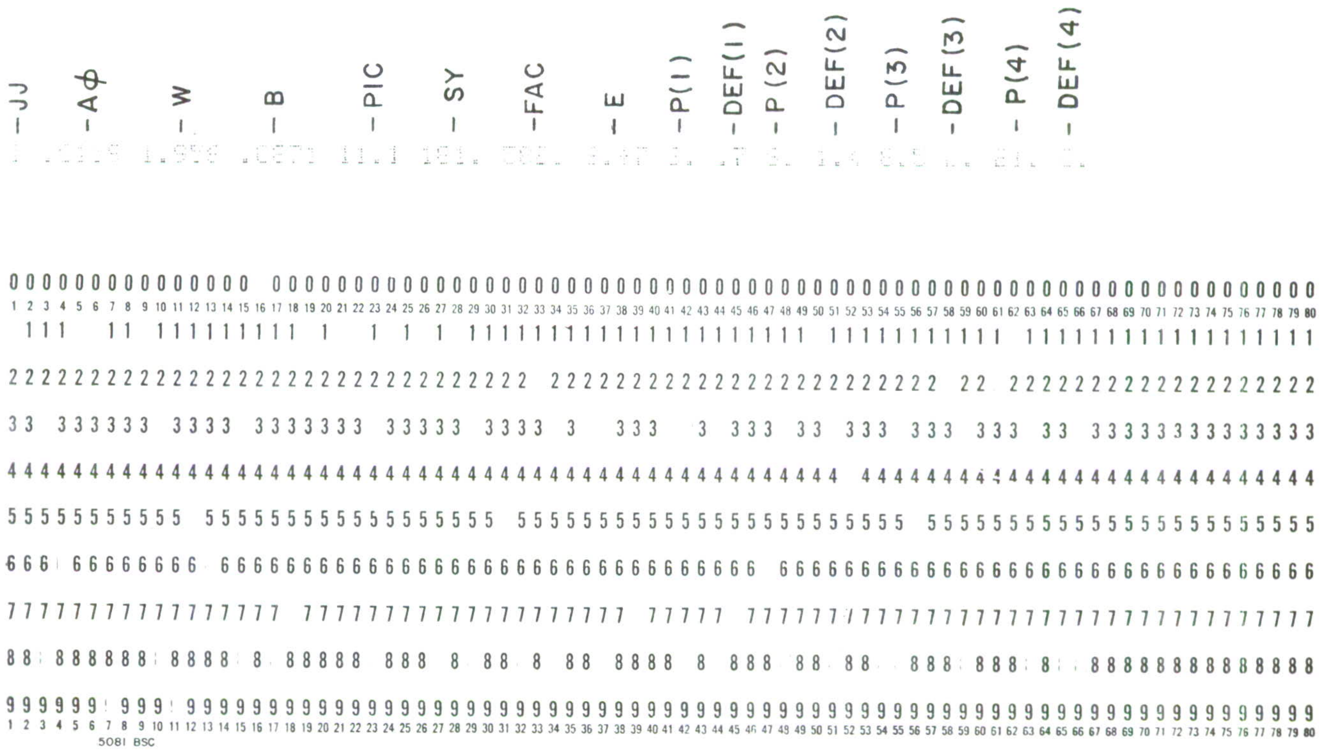
Card No. 2

```
1.23184  -.212053  -.0774244  0.  .0019483
```



JJ=1: Actual test data is read in on subsequent cards, beginning with card number 3. Each set of test data is begun in column one and may be presented on several successive cards, as necessary. A value must be given for every parameter listed on the card below. If applicable, 0.0 may be inserted as the value for any of these items.

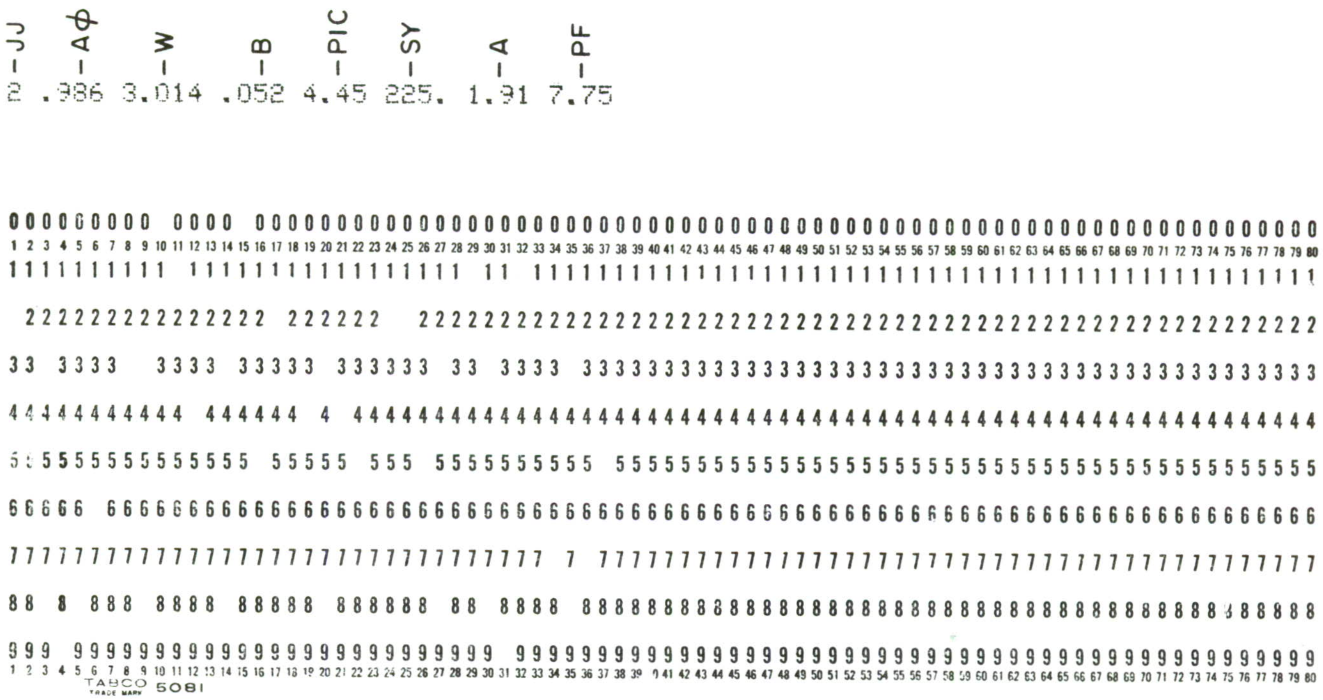
Sample Data Card for JJ=1



NOTE: This data card yields the first two lines of results in Table 7.

JJ=2: For calculations not requiring the compliance calculation of the critical crack length, the following sample data card is appropriate. The one space between data items in Columns 1 to 70 is required.

Sample Data Card for JJ=2



The following is an abbreviated glossary for the symbols shown on the sample data cards. No attempt has been made to define all the symbols used in the source program and the subroutines VDECOM and DECDCP.

LIST OF SYMBOLS (INPUT DATA)

Fortran Symbol	Analytical Symbol	Definition
Aϕ	$2a_o$	Total initial crack length
W	w	Width
B		Thickness
PIC		"Pop-in" load (Kips)
SY		Yield Stress (KSI)
FAC		Total magnification of the compliance gage*
E	E	Modulus of Elasticity (psi)
P(1), P(2), P(3)		Loads (Kips) on linear portion of compliance curve
DEF(1), DEF(2), DEF(3)		Deflections (inches of chart) corresponding to P(1), P(2), P(3)
P(4) or PF		Load at Fracture (Kips)
DEF (4)		Deflection at fracture (inches of chart)
A	2a	Total critical crack length

* A gage with a 250X microformer and a gage lever ratio of 2 would have FAC = 500.

DATA OUTPUT

The computer program supplies a data output as shown in Table 7. The first line of a single test set contains K_{Ic} data while the second line contains K_c data. The "nominal ratio" as used here is equivalent to the "notch strength ratio."

SOURCE PROGRAM AND SUBROUTINES

The complete Fortran II program which consists of the source program and two closed subroutines, VDECOM and DECDCP, is presented in Table 8.

TABLE 7. EXAMPLE OF COMPUTER PROGRAM OUTPUT

```
 CRACK LENGTH    WIDTH  THICKNESS   LOAD   GROSS   NOMINAL   NET   YIELD  NOMINAL  NET   LENGTH/  PLASTIC   TOUGHNESS  K
INITIAL  FINAL                            STRESS   STRESS  STRESS STRESS  RATIO   RATIO  WIDTH    ZONE    BASIC  CORRECTED

 0.612           1.956   0.0871    11.10   65.15    94.81   94.81 181.00           0.52   0.31   0.0236    66.66     69.69
 0.612   1.066   1.956   0.0871    21.00  123.26   179.38  270.98 181.00   0.99    1.50          0.1664   185.10    185.10

 0.546           1.969   0.0880    10.80   62.33    86.23   86.23 181.00           0.48   0.28   0.0186    59.65     61.96
 0.546   1.016   1.969   0.0880    21.45  123.79   171.26  255.72 181.00   0.95    1.41          0.1541   178.10    178.10

 0.640           1.964   0.0870     8.40   49.16    72.91   72.91 175.00           0.42   0.33   0.0146    51.63     53.04
 0.640   1.067   1.964   0.0870    20.40  119.39   177.06  261.28 175.00   1.01    1.49          0.1666   179.06    179.06

 0.575           1.961   0.0882     4.60   26.60    37.64   37.64 197.00           0.19   0.29   0.0029    26.24     26.40
 0.575   0.614   1.961   0.0882     5.08   29.37    41.57   42.75 197.00   0.21    0.22          0.0038    30.10     30.32

 0.594           1.958   0.0862     4.70   27.85    39.99   39.99 208.00           0.19   0.30   0.0029    28.01     28.17
 0.594   0.621   1.958   0.0862     5.23   30.99    44.50   45.37 208.00   0.21    0.22          0.0038    31.97     32.20

 0.524           1.959   0.0888     4.96   28.51    38.93   38.93 206.00           0.19   0.27   0.0027    26.69     26.84
 0.524   0.568   1.959   0.0888     5.61   32.25    44.04   45.42 206.00   0.21    0.22          0.0038    31.59     31.83

 0.605           1.955   0.0872     6.50   38.13    55.22   55.22 196.00           0.28   0.31   0.0064    38.76     39.24
 0.605   0.662   1.955   0.0872     7.65   44.87    64.99   67.84 196.00   0.33    0.35          0.0099    48.12     49.00

 0.640           1.961   0.0873    10.80   63.09    93.62   93.62 181.00           0.52   0.33   0.0232    66.25     69.14
 0.640   0.996   1.961   0.0873    21.05  122.96   182.48  249.78 181.00   1.01    1.38          0.1476   174.29    174.29

 0.624           1.957   0.0879     8.10   47.09    69.11   69.11 181.00           0.38   0.32   0.0121    48.72     49.84
 0.624   1.031   1.957   0.0879    21.60  125.57   184.29  265.38 181.00   1.02    1.47          0.1631   183.23    183.23
```

TABLE 8. SOURCE COMPUTER PROGRAM

```
CCALC CENTER NOTCH FRACTURE TOUGHNESS AND COMPLIANCE GAGE CALCULATIONS
      DIMENSION AFIT(7), BFIT(7),  P(4), V(3), DEF(4), Y(3), INT(10),
     1 DEC(10)
      PI = 3.14159
      JTAPE = 2
      NTAPE = 3
C      READ IN COEFFICIENTS FOR COMPLIANCE CURVES
C       Y = F(X)
      READ INPUT TAPE JTAPE, 1000, ( AFIT(I), I = 1, 7)
C       X = F(1./Y)
      READ INPUT TAPE JTAPE, 1000, ( BFIT(I) , I = 1, 7)
      WRITE OUTPUT TAPE NTAPE,4000
    5 N = 1
      KPASS = 1
      CALL VDECOM( N, INT, DEC, KPASS)
      JJ = INT(1)
      N = 7
      KPASS = 3
      CALL VDECOM( N, INT, DEC, KPASS)
      A0 = DEC(1)
      AO = A0
      W = DEC(2)
      B = DEC(3)
      PIC = DEC(4)
      SY = DEC(5)
      FAC = DEC(6)
      E = DEC(7)
      A = DEC(6)
      PF = DEC(7)
      NN = 0
      GO TO(15,35),JJ
   15 N = 8
      KPASS = 3
      CALL VDECOM( N, INT, DEC, KPASS)
      DO 10 I = 1, 4
      K = 2 * I
      P(I) = 1000.*DEC(K-1)
   10 DEF(I) = DEC(K)
C      COMPUTE AVERAGE VALUES OF Y AT Z
      YSUM= 0.
      DO 20 I = 1, 3
      V(I) =  0.5 * DEF(I) / FAC
      Y(I) =  E * V(I) * B / P(I)
   20 YSUM=YSUM + Y(I)
      YAVG=YSUM/3.
      YFRAC=E*B*DEF(4)/(2.*FAC*P(4))
      Z = PI * AO / ( 2. * W)
C      EVALUATE COMPLIANCE POLYNOMIAL AT Z
      YFIT = AFIT(1)
      DO 25 I = 1, 6
   25 YFIT = YFIT + AFIT(I+1) * Z**I
C      COMPUTE DIFFERENCE BETWEEN Y VALUES
      YDIFR = YAVG - YFIT
C      CALCULATE ZNEW AT FRACTURE FROM ADJUSTED VALUE OF Y
      YNEW=YFRAC - YDIFR
```

TABLE 8. (Continued)

```
      ZNEW = BFIT(1)
      DO 30 I = 1, 6
   30 ZNEW = ZNEW + BFIT (I+1)  /(YNEW**I)
C      COMPUTE NEW FRACTURE CRACK LENGTH
      A = 2. * W * ZNEW / PI
      PF=P(4)/1000.
C      COMPUTE THE STRESS AND FRACTURE-TOUGHNESS
   35 AKIC = 0.0
      SG = PIC/(W*B)
      SNF = PIC/(B*(W-AO))
      SN1 = SNF
      SN2 = PIC/(B*(W-A1))
      SRN = SN2/SY
      PA = PI*AO/(2.*W)
      BKS = SINF(PA)/COSF(PA)*W*SG**2
      AOW = AO/W
      SR = SNF/SY
      RP = BKS/(2.*PI*SY**2)
      BK1 = SQRTF(BKS)
C      EVALUATE THE EQUATION LIMITATION
      GOYS = (SG/SY)**2
      QM = SQRTF(2./GOYS - 1.)
      PAM = ATANF(QM) - QM*GOYS/2.
      IF(PAM-PA)39,40,40
   39 AKIC = BK1
      GO TO 45
C      COMPUTE THE PLASTIC ZONE FRACTURE-TOUGHNESS
   40 PAP = PA + BKS/(2.0*W*SY**2)
      PKS = SINF(PAP)/COSF(PAP)*W*SG**2
      BK = SQRTF(BKS)
      AKIC = SQRTF(PKS)
      BKS = PKS
      IF(AKIC-BK-.005)44,40,40
   44 RP = PKS/(2.*PI*SY**2)
   45 IF(NN)50,50,60
   50 WRITE OUTPUT TAPE NTAPE,2000,AO,W,B,PIC,SG,SN1,SNF,SY,SR,AOW,RP,
     1  BK1,AKIC
      A1 = AO
      AO = A
      PIC = PF
      NN = 1
C      REPEAT FOR PLANE-STRESS TOUGHNESS
      IF(AO)5,5,35
   60 WRITE OUTPUT TAPE NTAPE,3000,A1,AO,W,B,PIC,SG,SN2,SNF,SY,SRN,SR,
     1  RP,BK1,AKIC
      GO TO 5
 1000 FORMAT(  7F10.5)
 2000 FORMAT(/,F7.3,F15.3,F9.4,F8.2,F7.2,F9.2,F8.2,F7.2,F14.2,F8.2,F9.4,
     1  2F9.2)
 3000 FORMAT(  F7.3,F8.3,F7.3,F9.4,F8.2,F7.2,F9.2,F8.2,3F7.2,F17.4,
     1  2F9.2)
 4000 FORMAT(1H1,116H CRACK LENGTH   WIDTH  THICKNESS  LOAD  GROSS   NOM
     1INAL  NET   YIELD  NOMINAL  NET   LENGTH/  PLASTIC   TOUGHNESS  K,
     2/,120H INITIAL  FINAL                               STRESS  STRESS  STR
     3ESS STRESS  RATIO  RATIO   WIDTH    ZONE    BASIC  CORRECTED)
      END
```

TABLE 8. (Continued)

```
      SUBROUTINE VDECOM(N ,     KARRAY,P      ,KPASS)     12/18/63

      SUBROUTINE VDECOM(N ,     KARRAY,P      ,KPASS)
      DIMENSION P(10)
      DIMENSION KINPUT(72), KARRAY(10), PARRAY(10),AINPUT(72),
     1          KOUTPT(72), AOUTPT(72)
      EQUIVALENCE (PLUS,IPLUS),(AMINUS,IMINUS), (DECPT,IDECPT),
     1             (COMMA,ICOMMA),(E, IE),( BLANK, IBLANK),
     2             (AINPUT, KINPUT), (AOUTPT, KOUTPT)
      KPASS = KPASS
C      J2 = INPUT TAPE
      J2 = 2
C      J4 = SCRATCH TAPE
      J4 = 4
      GO TO ( 2, 2, 2, 3), KPASS
    2 REWIND J4
    3 NUMDCP = N
      NEX =1
      N1 = 1
      L = 1
      GO TO (1, 10, 50, 50), KPASS
    1 CONTINUE
C      SET UP CHARACTERS FOR LATER TEST
B     PLUS   = 206060606060
B     AMINUS = 406060606060
B     DECPT  = 336060606060
B     COMMA  = 736060606060
B      E     = 256060606060
B     BLANK  = 606060606060
C      READ ALPHANUMERIC CHARACTERS
    5 READ INPUT TAPEJ2,1000, (AINPUT(J),J=1,72)
      I=1
      GO TO (10,10, 50, 50), KPASS
C      DECOMPOSITION OF INTEGERS
   10 DO 21 N = N1, NUMDCP
      N1 = N
C      SEARCH FOR START OF NUMBER
  101 IF (KINPUT(I) - IBLANK) 102, 11, 102
  102 IF (KINPUT(I) - ICOMMA) 12 , 11,  12
   11 I= I+1
      IF( I -72)101,101, 5
C      SELECT INTEGERS
   12 L1 = L
      M = 0
      DO 20 J=1,6
      KOUTPT(L) = KINPUT(I)
      IF( KINPUT(I) - IMINUS) 122, 120, 122
  122 IF( KINPUT(I) - IPLUS) 123, 120, 123
  120 M = 1
  123 L = L + 1
      I= I+1
      IF(KINPUT(I) -IBLANK)121 ,13 ,121
  121 IF(KINPUT(I) -ICOMMA) 20 ,13 , 20
C      RIGHT ADJUST IN FIELD
   13 IF( J-6) 14,21,14
   14 KDO = J - M
      DO 15 K = 1, KDO
      L2 = L1 + 6 - K
```

TABLE 8. (Continued)

```
      SUBROUTINE VDECOM(N ,     KARRAY,P      ,KPASS)     12/18/63

      L3 = L1 + J    - K
   15 KOUTPT(    L2 )= KOUTPT(   L3 )
      L = L1 + 6
      KDO = 6-J  + M
      KGO = 1 + M
      DO 16 K = KGO, KDO
      L4 = L1 + K    -1
   16 KOUTPT(  L4)   = 0
      GO TO 21
   20 CONTINUE
   21 CONTINUE
      IEND = 6* NUMDCP
C       WRITE ALPHANUMERIC CHARACTERS
      WRITE OUTPUT TAPEJ4,1000, (AOUTPT(J), J=1, IEND)
      REWINDJ4
C       READ INTEGER LIST
      READ INPUT TAPEJ4,1001,    (KARRAY(J), J=1,NUMDCP)
      REWINDJ4
   40 RETURN
   50 CALL DECDCP        ( IPLUS, IMINUS, IDECPT, ICOMMA, IE, IBLANK,
     1 KINPUT, NUMDCP, PARRAY, I, L, NEX, N1, KPASS)
      NEX = NEX
      GO TO(30,5), NEX
   30 DO 31 J = 1, NUMDCP
   31 P(J) = PARRAY(J)
      GO TO 40
 1000 FORMAT(72A1)
 1001 FORMAT(11I6)
      END(1,1,0,0,0,1,1,1,0,1,0,0,0,0,0)
```

TABLE 8. (Continued)

```
      SUBROUTINE DECDCP( IPLUS, IMINUS, IDECPT, ICOMMA, IE, IBLANK,   12/18/63

      SUBROUTINE DECDCP( IPLUS, IMINUS, IDECPT, ICOMMA, IE, IBLANK,
     1 KINPUT, NUMDCP, PARRAY, I, L, NEX, N1, KPASS)
      EQUIVALENCE (AOUTPT, KOUTPT)
      DIMENSION  AOUTPT(72), KOUTPT(72), PARRAY(10) , KINPUT(72)
      NEX = NEX
C      J2 = INPUT TAPE
      J2 = 2
C      J4 = SCRATCH TAPE
      J4 = 4
      M = L
      GO TO (50,51),NEX
C      DECOMPOSITION OF DECIMAL AND EXPONENTIAL NUMBERS
C      LIMIT DECOMPOSITION TO 6 NUMBERS
   50 IF(NUMDCP -6)503,503,502
  502 IDEC = 6
      IEND = 12*IDEC
      GO TO 504
  503 IDEC = NUMDCP
      IEND = 12* NUMDCP
  504 IF(I -72) 51,51,505
  505  NEX = 2
       GO TO 300
   51 NEX = 1
      DO 100  N= N1, IDEC
      N1 = N
C      SEARCH FOR START OF NUMBER
  510 IF(KINPUT(I)- IBLANK)  52, 53, 52
   52 IF(KINPUT(I)- ICOMMA) 54, 53, 54
   53 I= I + 1
      IF( I - 72) 510, 510, 505
   54 M1 = M
C      STORE NUMBERS UP TO DECIMAL POINT
  541 IF(KINPUT(I) - IDECPT) 55, 65, 55
   55 KOUTPT(M) = KINPUT(I)
      I= I +1
      M= M +1
      GO TO 541
C      TEST FOR END OF NUMBER OR EXPONENTIAL
   60 IF(KINPUT(I) - IE     ) 61, 70,61
   61 IF(KINPUT(I) - IPLUS  ) 62, 70,62
   62 IF(KINPUT(I) - IMINUS ) 63, 70,63
   63 IF(KINPUT(I) - ICOMMA ) 64, 80,64
   64 IF(KINPUT(I) - IBLANK ) 65, 80,65
C      STORE DECIMAL POINT AND NUMBERS
   65 KOUTPT(M) = KINPUT(I)
      I= I+1
      M= M+1
      GO TO 60
C      COMPLETE EXPONENTIAL FIELD THROUGH 8 LOCATIONS
   70 LDO = M1 + 7
      DO 71 J1= M, LDO
   71 KOUTPT(J1) = 0
      M = M1 + 8
C      STORE E IN LOCATION 9
      KOUTPT(M) = IE
      IF(KINPUT(I)- IE) 73,72,73
```

TABLE 8. (Continued)

```
      SUBROUTINE DECDCP( IPLUS, IMINUS, IDECPT, ICOMMA, IE, IBLANK,  12/18/63
   72 I= I+1
C      TEST FOR SIGN OF EXPONENT
   73 IF(KINPUT(I)-IMINUS) 74, 76,74
   74 IF(KINPUT(I)-IPLUS ) 75, 76 ,75
   75 KOUTPT(M+1) = IPLUS
      GO TO 77
C      STORE SIGN
   76 KOUTPT(M+1) = KINPUT(I)
      I=I+1
C      TEST FOR END OF EXPONENT
   77 IF(KINPUT(I+1) - IBLANK) 78, 79, 78
   78 IF(KINPUT(I+1) - ICOMMA) 791,79 ,791
   79 KOUTPT(M+2) = 0
      KOUTPT(M+3) = KINPUT(I)
      GO TO 792
  791 KOUTPT(M+2) = KINPUT(I)
      KOUTPT(M+3) = KINPUT(I+1)
  792 I= I+2
      M = M1 + 12
      GO TO 100
C      COMPLETE DECIMAL FIELD
   80 LDO = M1 + 11
      DO 81 J1 = M , LDO
   81 KOUTPT(J1) = 0
      M = M1 + 12
  100 CONTINUE
C      WRITE ALPHANUMERIC CHARACTERS
      WRITE OUTPUT TAPEJ4,1000,(AOUTPT(J),J=1, IEND)
      IF(NUMDCP - IDEC ) 201, 201, 200
  200 M = 1
      N1 = N1 + 1
      IEND = 12*(NUMDCP - 6)
      IDEC = NUMDCP
      GO TO 504
  201 GO TO( 202, 202, 202, 300), KPASS
  202 REWINDJ4
C      READ DECIMAL AND EXPONENTIAL LIST
      READ INPUT TAPE J4,1010,(PARRAY(J),J=1, NUMDCP)
      REWINDJ4
  300 L = M
      RETURN
 1000 FORMAT(72A1)
 1010 FORMAT(6F12.5)
      END(1,1,0,0,0,1,1,1,0,1,0,0,0,0,0)
```

APPENDIX II

COMPLIANCE METHOD ANALYSIS

From the theory of elasticity as presented by Timoshenko and Goodier (Reference 7), there is a stress function ϕ which satisfies the biharmonic equation $\Delta^4\phi=0$ and also satisfies boundary conditions such that the external forces may be considered as an extension of the internal stress distribution. If this is true then:

$$\sigma_x = \frac{\partial^2\phi}{\partial y^2}, \quad \sigma_y = \frac{\partial^2\phi}{\partial x^2} \quad \text{and} \quad \tau_{xy} = -\frac{\partial^2\phi}{\partial x\,\partial y}$$

where ϕ is a function of x and y and is called the Airy stress function.

Westergaard (Reference 8) has provided a two-dimensional stress analysis of a very large flat plate with tension applied in the y direction and a system of cracks along the x axis each of length 2a and center at $x=0, \pm L, \pm 2L \cdots$ Using Westergaard's notation, if the function ϕ is related to a complex function, we shall call it Z where

$$Z = Z(z) = Z(x+iy) \quad \mathrm{Re}\,Z + i\,\mathrm{Im}\,Z \tag{1}$$

and the pertinent values are given by the analytic function

$$Z = \frac{\sigma}{\sqrt{1-\left(\dfrac{\sin\left(\frac{\pi a}{L}\right)}{\sin\left(\frac{\pi z}{L}\right)}\right)^2}} \tag{2}$$

In Westergaard's notation,

$$Z' = \frac{dZ}{dz}$$

$$Z = \frac{d\bar{Z}}{dz}$$

$$\bar{Z} = \frac{d\bar{\bar{Z}}}{dz}$$

Applying the Cauchy Riemann conditions,

$$\frac{\partial\,\mathrm{Re}\,Z}{\partial x} = \frac{\partial\,\mathrm{Im}\,Z}{\partial y} = \mathrm{Re}\,Z', \text{ and } \frac{\partial\,\mathrm{Im}\,Z}{\partial x} = -\frac{\partial\,\mathrm{Re}\,Z}{\partial y} = \mathrm{Im}\,Z'$$

If the Airy function is defined as

$$\phi = \mathrm{Re}\ \bar{\bar{Z}} + y\ \mathrm{Im}\ \bar{Z}$$

and it satisfies the biharmonic equation

$$\frac{\partial^4 \phi}{\partial x^4} + \frac{2\partial^4 \phi}{\partial x^2\, \partial y^2} + \frac{\partial^4 \phi}{\partial y^4} = 0$$

then

$$\sigma_y = \frac{\partial^2 \phi}{\partial x^2} = \frac{\partial^2\, \mathrm{Re}\ \bar{\bar{Z}}}{\partial x^2} + y\, \frac{\partial^2\, \mathrm{Im}\ \bar{Z}}{\partial x^2}$$

Since

$$\frac{\partial^2\, \mathrm{Re}\ \bar{\bar{Z}}}{\partial x^2} = \mathrm{Re}\ Z$$

and

$$y\, \frac{\partial^2\, \mathrm{Im}\ \bar{\bar{Z}}}{\partial x^2} = y\ \mathrm{Im}\ Z'$$

Therefore,

$$\sigma_y = \mathrm{Re}\ Z + y\ \mathrm{Im}\ Z' \qquad (3)$$

By similar steps,

$$\sigma_x = \mathrm{Re}\ Z - y\, \mathrm{Im}\ Z' \qquad (4)$$

$$\tau_{xy} = -y\ \mathrm{Re}\ Z' \qquad (5)$$

The displacement, v, in the y direction for a plane strain situation is given by the equation.

$$Ev = 2\ (1-\nu^2)\, \mathrm{Im}\ \bar{Z} - (1+\nu)\ y\ \mathrm{Re}\ Z$$

where ν is Poisson's ratio and E is the modulus of elasticity.

It has been shown by Irwin (Reference 9) that the above stress analysis is a good approximation to the stress state in a centrally cracked sheet specimen whose vertical and horizontal axes of symmetry are taken as the y and x axes respectively. The specimen, with width w = L, is regarded as one unit of the crack system, and therefore the specimen edges are at x = ±L/2 and the crack extends from x = -a to x = +a. Boundary conditions require the stresses σ_y and τ_{xy} to be zero along the borders of the crack and the stresses σ_x and τ_{xy} to be zero along the side boundries. All these conditions are fulfilled except the condition that $\sigma_x = 0$. Irwin remedied this by rewriting σ_x as

$$\sigma_x = \mathrm{Re}\ Z - y\ \mathrm{Im}\ Z' - \sigma_{ox} \qquad (6)$$

where σ_{o_x} is a constant stress adjusted so that

$$\int_0^\infty \sigma_x \, dy = 0 \text{ at } x = \pm \frac{L}{2} .$$

The constant σ_{o_x} does not make σ_x zero at all points on the side boundries, but it does reduce σ_x to a very small value. It is assumed here that this deviation from an exact solution results in errors much smaller than those resulting from the departure from linear elasticity theory for finite strains.

Irwin modified the equation for the displacement in the y direction to make it applicable to a generalized plane stress condition. This equation is

$$Ev = 2 \, \mathrm{Im} \, \bar{Z} - (1 + \nu) \, y \, \mathrm{Re} \, Z \qquad (7)$$

It is now possible to derive an expression for compliance at the specimen edges. The edges of the specimen are at x = ±L/2. Therefore, z = ±L/2 + iy where y is 1/2 of the specimen gage length

Integration of $\bar{Z} = \int Z dz$ utilizing Equation (2) gives

$$\bar{Z} = - \frac{L\sigma}{\pi} \sin^{-1} \left(\frac{\cos \frac{\pi z}{L}}{\cos \frac{\pi a}{L}} \right) + C \qquad (8)$$

where C is a complex constant of integration to be evaluated for the known conditions at a = o. Utilizing the identities

$$\cos \left[\frac{\pi}{L} \left(\frac{L}{2} + iy \right) \right] = - i \sinh \frac{\pi y}{L}$$

$$\sin \left[\frac{\pi}{L} \left(\frac{L}{2} + iy \right) \right] = \cosh \frac{\pi y}{L}$$

and

$$- \sin^{-1} (-m) = i \sinh^{-1} (m)$$

and substituting in Equation 8, it is found that

$$\bar{Z} = \frac{iL\sigma}{\pi} \sinh^{-1} \left[\frac{\sinh \frac{\pi y}{L}}{\cos \frac{\pi a}{L}} \right] + \mathrm{Re} \, C + i \, \mathrm{Im} \, C \qquad (9)$$

Therefore,

$$\mathrm{Im}\,\overline{Z} = \frac{L\sigma}{\pi}\sinh^{-1}\left[\frac{\sinh\frac{\pi y}{L}}{\cos\frac{\pi a}{L}}\right] + \mathrm{Im}\,C \tag{10}$$

Also, when $x = \pm L/2$,

$$Z = \frac{\sigma}{\sqrt{1-\left(\dfrac{\sin\frac{\pi a}{L}}{\cosh\frac{\pi y}{L}}\right)^2}} \tag{11}$$

and it is real. Therefore, $\mathrm{Re}\,Z = Z$ at $x = \pm L/2$. The expression for the displacement v is found by substituting Equations 10 and 11 into Equation 7. In accordance with R. W. Boyle (Reference 2), the compliance v/σ, is expressed as a dimensionless parameter by dividing by the specimen width w and multiplying by Young's modulus. Now, by setting $L = w$, the equation for compliance becomes

$$\frac{Ev}{\sigma w} = \frac{2}{\pi}\sinh^{-1}\left(\frac{\sinh\frac{\pi y}{w}}{\cos\frac{\pi a}{w}}\right) + \frac{2\,\mathrm{Im}\,C}{\sigma w} - \frac{y}{w}\;\frac{(1.+\nu)}{\sqrt{1-\dfrac{\sin^2\frac{\pi a}{w}}{\cosh^2\frac{\pi y}{w}}}}$$

The term Im C is evaluated by knowing that when $a = o$ the specimen is simply an unnotched specimen, and $Ev/\sigma W$ is equal to y/w. The final equation

$$\frac{Ev}{\sigma w} = \frac{2}{\pi}\sinh^{-1}\left(\frac{\sinh\frac{\pi y}{w}}{\cos\frac{\pi a}{w}}\right) - \frac{y}{w}\;\frac{(1+\nu)}{\sqrt{1-\dfrac{\sin^2\frac{\pi a}{w}}{\cosh^2\frac{\pi y}{w}}}} + \frac{\nu y}{w} \tag{12}$$

To review the pertinent symbols in Equation 12, E is Young's modulus, v is one-half the specimen extension, σ is the gross stress calculated from the dimensions of the uncracked specimen, w is the specimen width, a is one-half the crack length, and y is one-half the specimen gage length.

It can be seen from Equation 12 that a plot of the dimensionless parameters $Ev/\sigma W$ vs $\frac{\pi a}{W}$ will yield a curve whose shape is constant regardless of the material tested. This is true because the factor y/W is constant for identical specimen geometries. The curve will shift up or down the $Ev/\sigma W$ axis for different materials because of different E values and the corresponding change in the extension factor $\nu y/W$.

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13. ABSTRACT

Plane strain fracture toughness and tensile properties were determined at room temperature, utilizing compliance and pop-in methods, for four high-strength steel alloys: PH 15-7 Mo, 17-7 PH, AM 350 and Vasco Jet 1000 (H-11). Fracture toughness values varied over a fairly wide range, with AM 350 having the highest at approximately 60.7 KSI in. and Vasco Jet 1000 (H-11) having the lowest at approximately 25 KSI in. A computer program used to reduce fracture toughness data was able to calculate critical crack length as well as fracture toughness when given either suitable compliance gage data or the measured test data. An acoustical pickup, used as an additional test monitor, is described. Analytical basis for the compliance method is presented.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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PH 15-7 Mo						
17-7 PH						
AM 350						
Vasco Jet 1000 (H-11)						
Fracture Toughness Compliance Method Analysis						
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