1-1-1982

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Recommended Citation

Durkee, Mark C., "Crack arrest fracture toughness of A36, A588, and A514 structural steels." (1982). *Theses and Dissertations.* Paper 1966.

CRACK ARREST FRACTURE TOUGHNESS
OF A36, A588, AND A514 STRUCTURAL STEELS

by

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A Thesis
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in
Mechanical Engineering

Lehigh University
1982

This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering.

May 14, 1982
(Date)

Professor in Charge

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ACKNOWLEDGEMENTS

I wish to extend my thanks to my advisor, Dr. Richard Roberts, for his advice, help, and guidance in the work leading to this report.

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ABSTRACT

The crack arrest fracture toughness, K_{Ia} of A36, A588, and A514 structural steels was investigated utilizing 25.4 mm and 50.88 mm thick specimens for each type of steel. A compact type specimen and a wedge loading system were utilized in the investigation. The test results show the thinner plates to be less tough than their corresponding thicker plates. Tests were performed over the temperature range $-62^{o}C$ to $17^{o}C$ ($-80^{o}F$ to $63^{o}F$). Comparison of the K_{Ia} data with K_{Id} data on the same plates suggests that K_{Ia} is not a lower bound toughness value as has been conjectured by other investigators.

I. Introduction

The purpose of this study is to investigate the crack-arrest fracture toughness of A36, A588, and A514 structural steels, both 25.4 mm and 50.8 mm in thickness. This fracture toughness value, K_{Ia}, is defined as the stress intensity factor at which a crack extending in plane strain will arrest. K_{Ia} is based on a static analysis at the end of a run-arrest segment of crack extension and assumes that K at the end of the event (about one millisecond after arrest) is essentially the same as it was at the moment of arrest (ref. 1). The procedure and analysis used here is that developed by Ripling (ref. 2). ASTM has not as yet standardized a test method for this particular toughness test.

K_{Ia} has been shown to be specimen insensitive (ref. 3). This in conjunction with a static stress analysis makes it possible to predict crack jump lengths in structures. K_{Ia} was used in just such a manner to predict crack jump lengths in a simulated LOCA (Loss of Coolant Accident) event. The measured and calculated values were found to be in excellent agreement (ref. 4).

It has also been suggested that K_{Ia} is a lower bound toughness value for a given temperature and thickness (ref. 5). This will also be investigated in this report.

II. Test Set-up

Specimen Preparation

Test specimens utilized in this investigation were of the MRL type as used by Ripling (ref. 6) shown in figure (1). A brittle weld bead was laid at the bottom of the slot in the specimen, Murex-Hardex-N welding electrodes were used for this step, with a starter notch then machined into the weld with an abrasive wheel (figure (2)). The 50.8 mm (2") thick specimens were machined to an $a_o/W=0.4$ whereas the 25.4 mm (1") specimens were machined to an $a_o/W=0.35$.

Instrumentation and Test Fixtures

A knowledge of displacement vs. time is required to evaluate both K_Q and K_{Ia} for a given test. Displacement was measured by an LVDT attached to the specimen as shown in figure (3); a strain gaged loading tup was also used to more clearly define the initial "pop." The test specimen was supported by two steel blocks which rested on the testing machine base.

Both displacement vs. time and load vs. time were simultaneously recorded by a digital oscilloscope with disk memory for later plotting. A typical test set-up is shown in figure (4).

III. Test Procedure

The procedure utilizes the specimen configuration shown in figure (1) with a three piece wedge loading system (figure (5)). The test set-up is shown in figure (6).

The specimen is first fitted with a mounting assembly for an LVDT. This is attached to the edge of the specimen and is used to measure displacement at a specified distance from the load line during the test.

The specimen is then cooled to the desired temperature in a methanol bath cooled with liquid nitrogen. When the desired temperature is reached the specimen is removed from the bath, fitted with the LVDT and wedge assembly, with the wedge then being driven into the specimen. The deflection vs. time and the load vs. time are both recorded digitally and stored for later plotting. A typical plot is shown in figure (7). The whole procedure, from removal from the bath to test completion, takes about one minute.

During the test if there is a crack initiation, run, and arrest, the deflection vs. time and the load vs. time plots show sudden, quite apparent jumps (figure (7)). The value of deflection at this jump along with a_o/W defines K_Q. The final crack lengths are determined by heat tinting the specimens at 300°C for 1½ hours, cooling them in liquid nitrogen, and breaking them open to measure the crack length.

IV. Calculation of K_Q and K_{Ia}

The K expression used in this investigation was experimentally derived (ref. 7) and is given by:

$$\frac{K\sqrt{W}}{E\Delta}\left(\frac{B_N}{B}\right)^{\frac{1}{2}} = \frac{2.2434(1.7162-0.9x+x^2)\sqrt{1-x}}{(9.85-0.17x+11.0x^2)}$$

where

W = distance from center of loading hole to end of specimen
E = Young's modulus
Δ = displacement measured at 0.25W
B_N = net specimen thickness on side-groove plane
B = gross specimen thickness
x = a/W
a = crack length

In evaluating K_Q or K_a two conditions must be met (ref. 8):

(1) A "pop-in" must occur. Evaluation of crack extension by stable tearing is beyond the intended scope of the K_a methodology.

(2) The crack tip plastic zone must be small enough, relative to in plane specimen dimensions, to preserve the applicability of linear elastic analysis. The limiting dimension is the uncracked ligament length ($W-a_f$) from the arrested crack front to the end of the specimen.

The criterion used was that the uncracked ligament length $(W-a_f)$ must be greater than, or equal to, eight plane-strain plastic zones. This expression is written

$$(W-a_f) \geq 4/3\pi\left(\frac{K_{Ia}}{(\sigma_o+\sigma_y)}\right)^2$$

where

σ_o = 206.8 MPa = strain rate correction for steels.

σ_y = 0.2 percent offset yield strength of the test material.

V. Material Qualities

Mechanical Properties

Six steel plates were used in the investigation. One each of A36, A588 and A514 50.8 mm (2") thick, and one each of A36, A588, and A514 25.4 mm (1") thick. Their mechanical properties are shown in table 1, mill test report, and table 2, Lehigh tensile results.

CVN Tests

CVN tests were performed on the test plates with results shown in figures (8) through (13). Note the 25°C (45°F) difference in the NDT's of 25.4 mm plate and the 50.8 mm plate of the A514.

VI. Test Results

General

A total of 100 specimens were tested in this investigation, 61 50.8 mm thick specimens and 39 25.4 mm thick specimens. Of the 100 specimens tested, 50 did not yield usable results and are broken down as follows:

Reason Test Was No Good	No. of Specimens Lost
Crack arrested out of plane	8
No "pop"	14
Specimen broke in two	13
Precompressed specimens*	6
Uncracked ligament length not adequate	3
Other (lost on scope, etc.)	6
	50 Total

*Precompressed specimens tended to yield unusually high K values for a given temperature, so these values were subsequently dropped.

Virtually all of the specimens that broke in two were A514.

Most of the specimens tested yielded very high K_Q values, on the order of 219 to 274 $MPa\sqrt{m}$ (200 to 250 $KSi\sqrt{In.}$) This resulted in most of the a_f/W values falling in the range 0.8 to 0.9, bringing the final crack length very close to the back of the specimen.

Using the requirement of 8 plane strain plastic zones, as stated earlier, as a minimum for the uncracked ligament length, all but 3 specimens meet this validity requirement.

A possible explanation for the high K_Q values could be that the notches machined in the weld were not made sharp enough. A blunt notch would yield a higher K_Q than a sharp notch. Actual test results are shown in Table 3.

A36 Tests. The graphs of K_{Ia} versus temperature for the 25.4 mm and 50.8 mm specimens are shown in figures (14) and (15). As can be seen, both curves show a downward sloping trend as temperature decreases. The K_{Ia} data acquired from the 50.8 mm specimens compares quite favorably with that reported by Ripling (ref. 9) for 50.8 mm thick A36 specimens.

When the curves are replotted so that NDT's are referenced to zero and compared, figure (16), one sees that the 25.4 mm curve lies below the 50.8 mm curve.

A514 Tests. The graphs of K_{Ia} versus temperature for the 25.4 mm and the 50.8 mm specimens are shown in figures (17) and (18). Concerning the 50.8 mm curve the most notable feature is the limited temperature range over which the tests were performed. This is because cracks could not be made to run above -26°C(-15°F), and no crack arrested at temperatures below -45°C (-50°F).

All but one specimen broke in two at -45°C, thus the reason for only one data point at this temperature. When the curves are referenced to their respective NDT's and compared, fig. (19), we again see that the 50.8 mm curve lies above the 25.4 mm curve.

One thing to be noted about the A514 tests is the peculiar characteristics of the specimens when tested. When tested usually two small, but audible, "pops" are heard. These show up on the oscilloscope trace as very small displacement changes with little or no load drop. These two small pops are then followed by a loud "pop" with a corresponding significant load drop and run-arrest.

These small "pops" can probably be attributed to the laminations present in this material. When the specimens are broken open one can see where the laminations separated near the starter notch. There are usually two major laminations present, thus accounting for the first two "pops."

A588 Tests. Plots of K_{Ia} versus temperature for the 25.4 mm and the 50.8 mm specimens are shown in figures (20) and (21). A curve was not fit to the 25.4 mm data due to the scatter.

When the plots are referenced to their respective NDT's and compared, fig. (22), the previous trend of the

25.4 mm K_{Ia} curve lying below the 50.8 mm curve appears to hold true as most of the 25.4 mm data falls below the 50.8 mm curve.

Comparison of K_{Ia} and K_{Id}

It has been suggested that K_{Ia} might be a minimum toughness value for a given temperature and specimen thickness (ref. 10). For this reason the K_{Ia} data acquired is being compared with K_{Id} results that were performed on the same plates used for the K_{Ia} tests. The K_{Ia} results are also compared to a calculated K_{Id} given by the expression (ref. 11) $K_{Id} = \sqrt{5E(CVN)}$

where E = Young's modulus

CVN = Impact energy

referred to hereafter as K_{Id}(CVN).

The results of these comparisons are shown in figures (23) through (28).

For the 25.9 mm A36 specimens, fig. (23), the K_{Ia} values are seen to lie above the K_{Id} values as well as the K_{Id}(CVN) curve. For the 50.8 mm A36 specimens, fig. (24), the K_{Ia} and K_{Id} data are grouped together; however, the K_{Ia} data still lie above the K_{Id}(CVN) curve.

For the 25.4 mm A588 specimens, fig. (25), the K_{Ia} values again lie above both the K_{Id} data and K_{Id}(CVN) curve. The same holds true for the A588 50.8 mm results, fig. (26).

When we look at the A514 results, however, we get a different trend. In both the 25.4 mm and the 50.8 mm cases, figures (27) and (28), we see that the K_{Id} values lie above the K_{Ia} values.

From the above observations one might draw the conclusion that K_{Ia} is not a lower bound toughness value as only the A514 steel seemed to exhibit this trait. Also, any attempt to estimate K_{Ia} by approximating K_{Ia} to K_{Id} by using $\sqrt{5E(CVN)}$ would yield, at best, a conservative result. (This approximation comes about as K_{Ia} is thought to be less than or equal to K_{Id} (ref. 12).

VII. Summary and Conclusions

1. The thinner plates, for all three materials, yielded lower K_{Ia} curves than the thicker plates.

2. Most specimens tested yielded very high K_Q values. This was probably due to the notch machined into the weld not being sharp enough.

3. The A514 (50.8 mm) specimens showed a very small temperature range where results could be obtained as specimens at -45°C and below, with the exception of one specimen, broke in two. This can probably be attributed to a high K_Q due to a blunt notch.

4. The suggestion that K_{Ia} is a lower limit toughness value for a given temperature and specimen thickness does not in general appear to be true as three of the plates tested show this not to be the case. However, at temperatures below NDT it has been conjectured that K_{Ia} should be larger than K_{Id} because the fatigue crack used in the K_{Id} test may provide a smoother initial fracture surface and less resistance to crack extension (ref. 13).

5. The use of the expression $K_{Ia} \approx \sqrt{5E(CVN)}$ would at best yield conservative results on K_{Ia}.

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TABLE 1

Summary - Mill Test Reports

MATERIAL	THICKNESS (mm)	MANUFACTURER	CVN TEST TEMP, °C	CVN RESULTS (JOULES)	σ_y (MPa)	σ_u (MPa)	ELONGATION (T)
A36	50.8	USS	4.4	42,48.8,50.2	291.6	578.1	23
A514	50.8	BSC	-17.7	29.8,27.1,31.2	835.6	892.2	20
A588	50.8	USS	4.4	25.7,25.7,28.4	350.9	552.2	24
A514	25.4	BSC	-17.7	32.5,32.5,29.8	717.7	801.8	36
A588	25.4	USS	4.4	27.1,96.1,47.4	455.8	661.9	19
A36	25.4	USS	4.4	17.6,91.4,23	314.4	464.7	26

TABLE 2

Summary - Lehigh Tensile Results

MATERIAL	THICKNESS (mm)	(MPa)	(MPa)	ELONGATION (%)	REDUCTION OF AREA (%)	NDT(°C)
A36	50.8	267.5	543.3	29	61	-5
A588	50.8	328.8	535.0	31	69	-10
A514	50.8	886.0	943.9	17	57	-50
A36	25.4	227.5	459.2	35	66	-10
A588	25.4	441.3	648.1	26	65	-15
A514	25.4	715.7	808.1	18.5	34	-75

TABLE 3

A36 (50.8 mm) Test Specimen Summary

SPECIMEN NUMBER	(°C) TEST TEMP.	(mm) Δ_o	(mm) Δ_f	(MPa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UA2(D3-D7)	R.T.							No pop.
UA2(D8-D6)	R.T.							No pop.
UA2(C3-C7)	R.T.	1.95	2.05	322.2	99.4	0.85	24.46	Weld cracked after cycling. No lube on support base.
UA2(B7-B3)	R.T.	1.27	1.09					Arrested out of plane. Initiated at toe of weld.
UA2(C5)	0	1.67	1.95	228.4	89.3	0.88	19.40	
UA2(B5-B2)	0	1.87	2.05	254.3	105.7	0.83	76.87	
UA2(D7-D4)	0	2.18	2.41	294.3	107.4	0.87	21.08	
UA2(C8-C6)	-26	1.65	1.62	220.9	83.3	0.84	26.11	Displacement was neg. Crack went out of plane, very rough surface.
UA2(C8-C5)	-26	2.03	2.15	274.5	78.2	0.91	14.78	
UA2(B4-B7)	-26	1.34	1.39	184.0	58.3	0.88	18.92	

A36 (50.8 mm) - Continued

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UA2(D5-D1)	-45	1.72	2.05	233.5	72.0	0.92	13.71	Precompressed to K_Q = 94.7 MPa$\sqrt{m}$
UA2(B5-B1)	-45							Precompressed. Arrested out of plane.
UA2(C5-C1)	-45							Ran off scope. Precompressed.
UA2(C7-C4)	-45	1.70	2.18	228.7	51.6	0.96	6.22	
UA2(B8-B5)	0							No pop.
UA2(D8-D5)	0	2.23	2.66	300.5	89.5	0.92	13.98	
UA2(B8-B6)	-26	2.94	3.09	386.0	133.0	0.87	21.69	(Not valid) Uncracked leg. length not large enough
UA2(C7-C3)	-26	1.98	2.38	265.8	74.6	0.93	11.68	
UA2(D8-D7)	-45	1.11	1.11	150.2	34.8	0.93	10.66	No change in Δ at "pop." (Invalid)
UA2(B8-B7)	-45							Initiated at edge of weld. Arrested out of plane.

A588 (50.8 mm)

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UB2(C8-C5)	R.T.							No pop.
UB2(D5-D1)	R.T.	2.23	2.76	300.5	132.1	0.84	25.55	Weld cracked after cycling. No lube on support base.
UB2(C8-C6)	0							No pop.
UB2(B8-B5)	0	1.32	1.57	178.6	76.8	0.85	24.25	Precompressed to 169.9 MPa$\sqrt{m}$
UB2(B5-B2)	0	1.72	1.93	232.1	93.2	0.85	23.77	
UB2(D7-D3)	0	2.38	2.69	320.9	122.1	0.86	21.94	
UB2(B7-B3)	-26	1.70	1.95	229.8	84.1	0.88	19.96	
UB2(C8-C7)	-26	1.29	1.21	251.5	85.9	0.88	18.79	
UB2(B7-B4)	-26	1.85	2.05	165.7	59.0	0.86	22.09	
UB2(C7-C3)	-45	0.99	1.37	134.2	121.6	0.63	60.19	Precompressed to K_Q = 158.1 MPa$\sqrt{m}$
UB2(B8-B7)	-45	1.16	1.17	157.3	93.7	0.67	52.88	Precompressed to K_Q = 155.9 MPa$\sqrt{m}$
UB2(B8-B6)	-45							Arrested out of plane.
UB2(B5-B1)	-45	1.49	1.62	186.9	66.1	0.89	17.47	

A588 (50.8 mm) - Continued

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UB2(D7-D4)	0							No pop.
UB2(D5-D2)	0	1.65	1.80	221.9	76.5	0.88	19.05	
UB2(C5-C2)	-26	2.20	2.36	297.0	95.2	0.89	17.98	
UB2(C7-C4)	-26	1.90	2.13	265.1	81.7	0.90	16.38	
UB2(C5-C1)	-26	1.87	2.08	252.6	88.1	0.88	18.51	
UB2(D8-D5)	-45	0.91	1.01	122.8	50.3	0.86	21.33	
UB2(D8-D7)	-45	1.52	1.60	204.8	49.9	0.93	11.43	
UB2(D8-D6)	-45							Lost specimen. LVDT power supply not on.

A514 (50.8 mm)

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
BC2(C5-C1)	-26	0.43	0.53	59.7	28.0	0.83	27.17	Loading stopped momentarily. Possible multiple run arrest segments.
BC2(D5-D1)	-26	1.82	2.03	245.9	101.4	0.84	25.83	Possible multiple run arrest segments (one of the load drops shows no change in Δ)
BC2(D5-D2)	-26	2.66	4.54					Broke almost all the way through.
BC2(D5-D2)	-26							Broke all the way through. LVDT recalibrated.
BC2(D8-Dy	-45							Precompressed to K_Q = 215.1 MPa$\sqrt{m}$
BC2(D8-D6)	-45							Precompressed to K_Q = 72.3 MPa $\sqrt{m}$ Broke in two.
BC2(B7-B7)	-26							Broke in two.
BC2(D3-D7)	-26	1.49	2.03	201.4	87.4	0.87	20.37	Plot showed mult. pop.
BC2(D8-D5)	-26	1.47	1.39	197.9	123.8	0.61	64.13	Very irregular crack front. (see drawing w/plot)
BC2(B8-B8)	-45	0.81	1.19	105.2	37.2	0.93	11.63	

A514 (50.8 mm) - Continued

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa√m) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
BC2 *(B8-B8)	-45							Broke in two. (Had same number stamped on it as previous specimen)
BC2(B8-B7)	-45							Broke in two.
BC2(B5-B2)	-62							Broke in two.
BC2(C5-C2)	-62							Broke in two.
BC2(C7-C3)	-62							Broke in two.
BC2(C8-C7)	-39	1.57	1.93	211.7	51.3	0.95	16.76	
BC2(C8-C5)	-39	1.16	1.09	157.0	72.7	0.75	41.19	
BC2(C8-C6)	-34							Broke in two.
BC2(B7-B7)	-45							Broke in two.
BC2(D7-D4)	-45							Broke in two.

A36 (25.4 mm)

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_0	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UA1(C54)	R.T.	1.95	2.18	286.4	113.0	0.83	27.3	Invalid. Uncracked lig. length not long enough
UA1(C58)	R.T.							No pop.
UA1(B52)	R.T.	1.80	1.98	263.6	94.6	0.85	24.2	
UA1(C57)	0	1.70	2.13	249.2	58.6	0.94	8.66	
UA1(C56)	0							LVDT off scope.
UA1(B59)	0	2.13	2.20	311.9	84.7	0.90	16.51	
UA1(C55)	0							No pop.
UA1(B54)	0							No pop.
UA1(C53)	-26	2.51	2.59	367.6	139.8	0.82	30.15	Not valid, uncracked lig. length not long enough.
UA1(B56	-26							Problem with LVDT grips. Plot no good.
UA1(B53	-45	0.48	0.88	70.5	49.6	0.81	31.21	K_a/K_Q vs. $A_f/W \rightarrow$ not grouped with other points

A36 (25.4 mm) - Continued

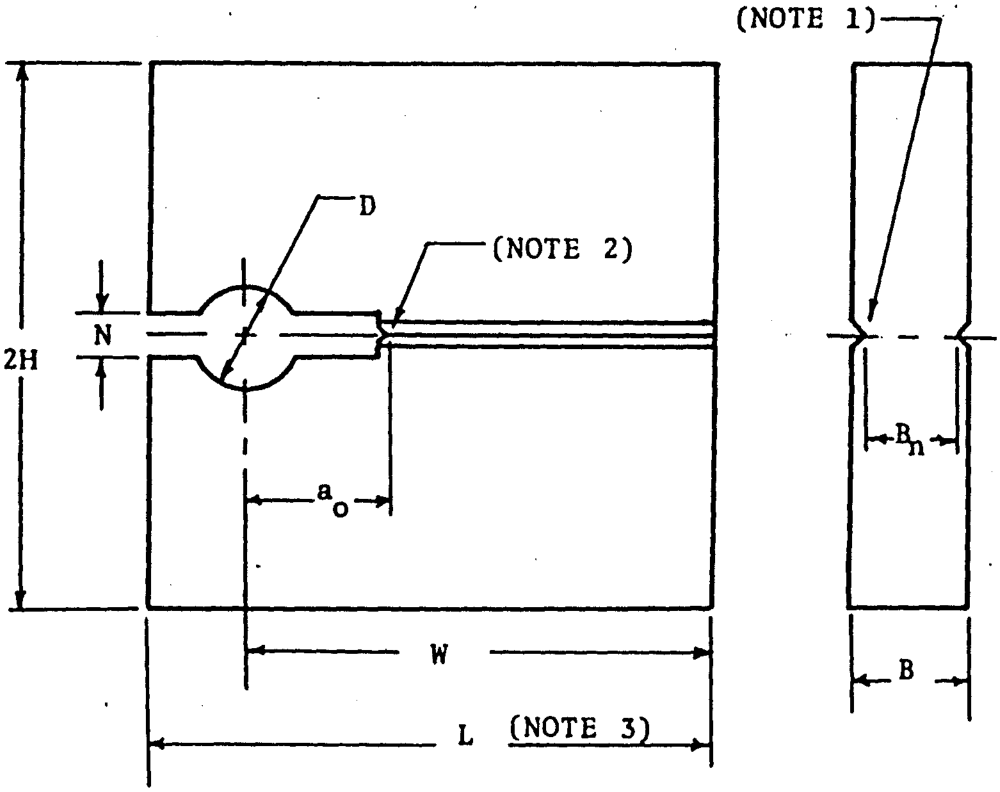
SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UA1(C52)	-45	0.38	0.73	55.7	47.8	0.76	39.67	K_a/K_Q vs. A_f/W → not grouped with other points
UA1(B55)	-26	1.82	2.33	267.9	68.3	0.94	9.80	(Invalid → uncracked lig. length not large enough.

A588 (25.4 mm) - Table 3 Continued

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
UB1(D54)	R.T.							Arrested out of plane.
UB1(A51)	R.T.	1.49	1.67	218.2	102.8	0.78	35.8	
UB1(A57)	R.T.	1.06	1.01	155.9	82.0	0.68	52.07	
UB1(D55)	0	2.28	2.54	333.0	.27.3	0.84	26.16	
UB1(D58)	0	0.98	0.55	70.5	66.8	0.47	86.76	
UB1(A52	0	1.16	1.06	157.0	61.6	0.80	32.38	
UB1(D52)	-26							Arrested out of plane.
UBI(D56)	-26	1.72	2.00	252.9	80.8	0.89	17.44	
UB1(A59)	-45							Arrested out of plane.
UB1(D57	-45	1.21	178.2	74.4	0.88	9.52		
UB1(A58)	-26	1.87	1.75	274.9	100.7	0.89	25.52	Crack front questionable.
UB1(D59)	-45	0.048	0.61	70.5	44.9	0.71	46.73	
UB1(A56)	-45							(No good) - Crack diverges to two paths, both out of plane.

A514 (25.4 mm) - Table 3 Continued

SPECIMEN NUMBER	(°C) TEST TEMP	(mm) Δ_o	(mm) Δ_f	(Mpa$\sqrt{m}$) K_Q	K_a	af/W	(mm) UNCRACKED LIG. LENGTH	COMMENTS
BC1(C58)	R.T.							No pop.
UB1(A59)	0	1.29	1.44	188.6	105.9	18.28	1.836	
BC1(C51)	0	2.89	2.97	389.2	197.9	19.05	1.620	
BC1(C55)	0							No pop.
BC1(C57)	0							No pop.
BC1(C59)	-26							No pop.
BC1(A58)	-26	0.50	0.58	74.3	51.3	16.0	2.333	Poss. multiple pop.
BC1(A55)	-45	1.16	1.65	170.8	38.9	24.38	0.250	
BC1(C56)	-45							No pop.
BC1(A57)	-62	0.71	1.01	103.9	53.5	20.82	1.187	
BC1(A54)	-62							Broke in two.
BC1(A56)	-26	1.32	1.57	193.1	89.9	20.32	1.268	
BC1(A51	-45	0.43	0.48	63.0	54.6	12.70	3.244	



$H=0.6W$ $B_n=0.75B$ $N=12.7mm$ $L=196.8mm$ $H=0.5L$

$D= 25.4mm$ $B=25.4mm$ or $50.8mm$

Note 1: 45° incl. angle, 0.25mm root radius face grooves.

Note 2: Machined notch in brittle weld deposit approx. 2mm deep, 0.25mm root radius.

Note 3: Dimension may be adjusted so that displacement gage can be mounted 0.25W from load line.

Figure1 - MRL type specimen

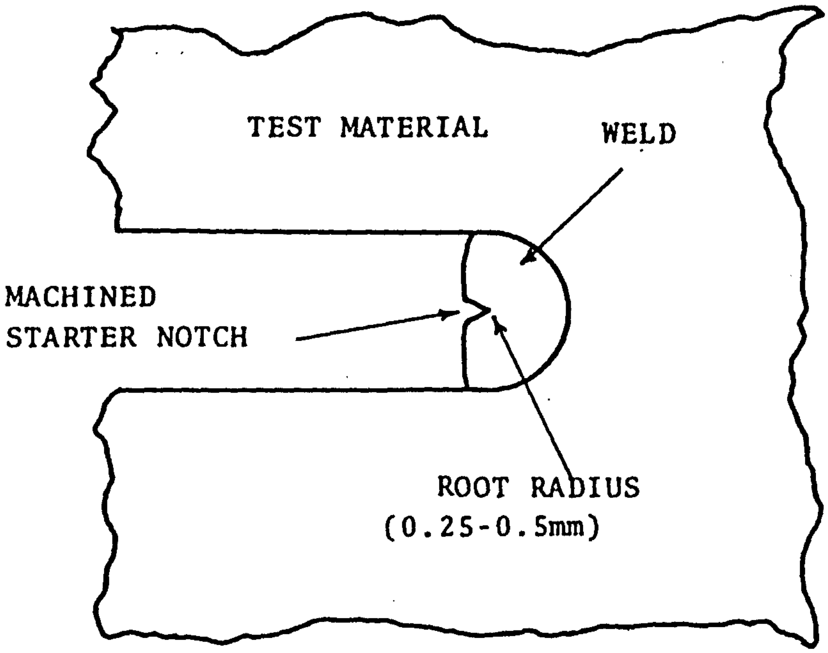


Figure 2- Detail of machined notch in brittle weld

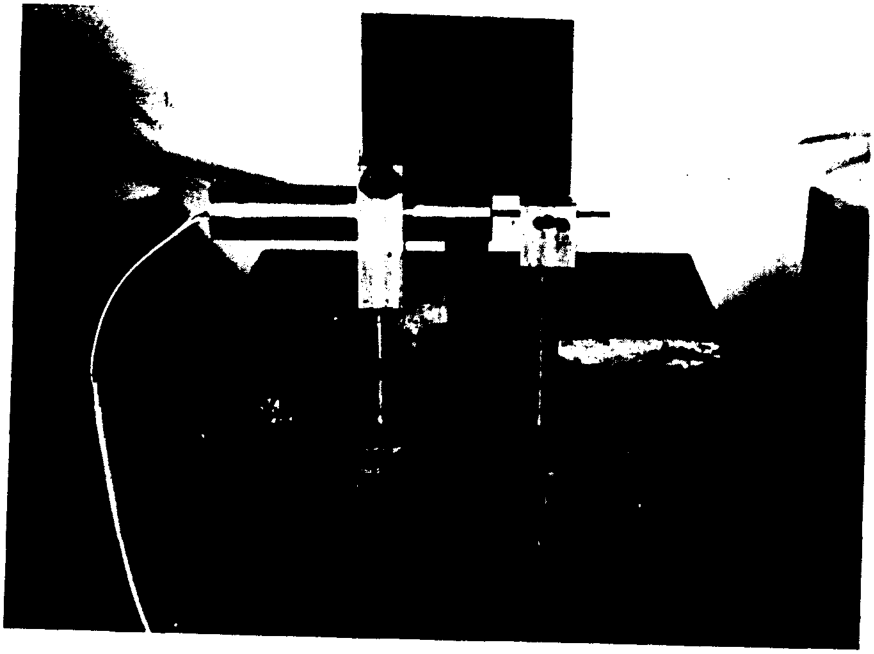


Figure 3 - LVDT attached to specimen.

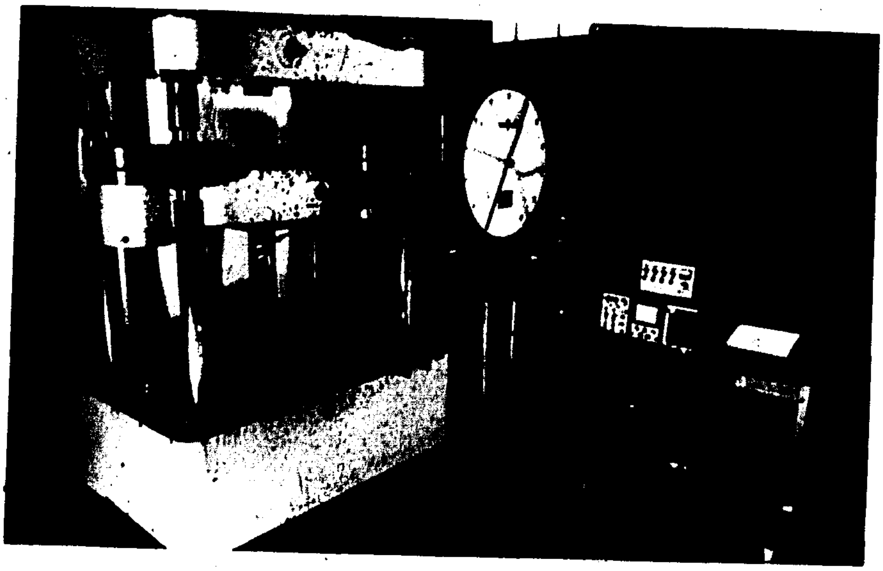
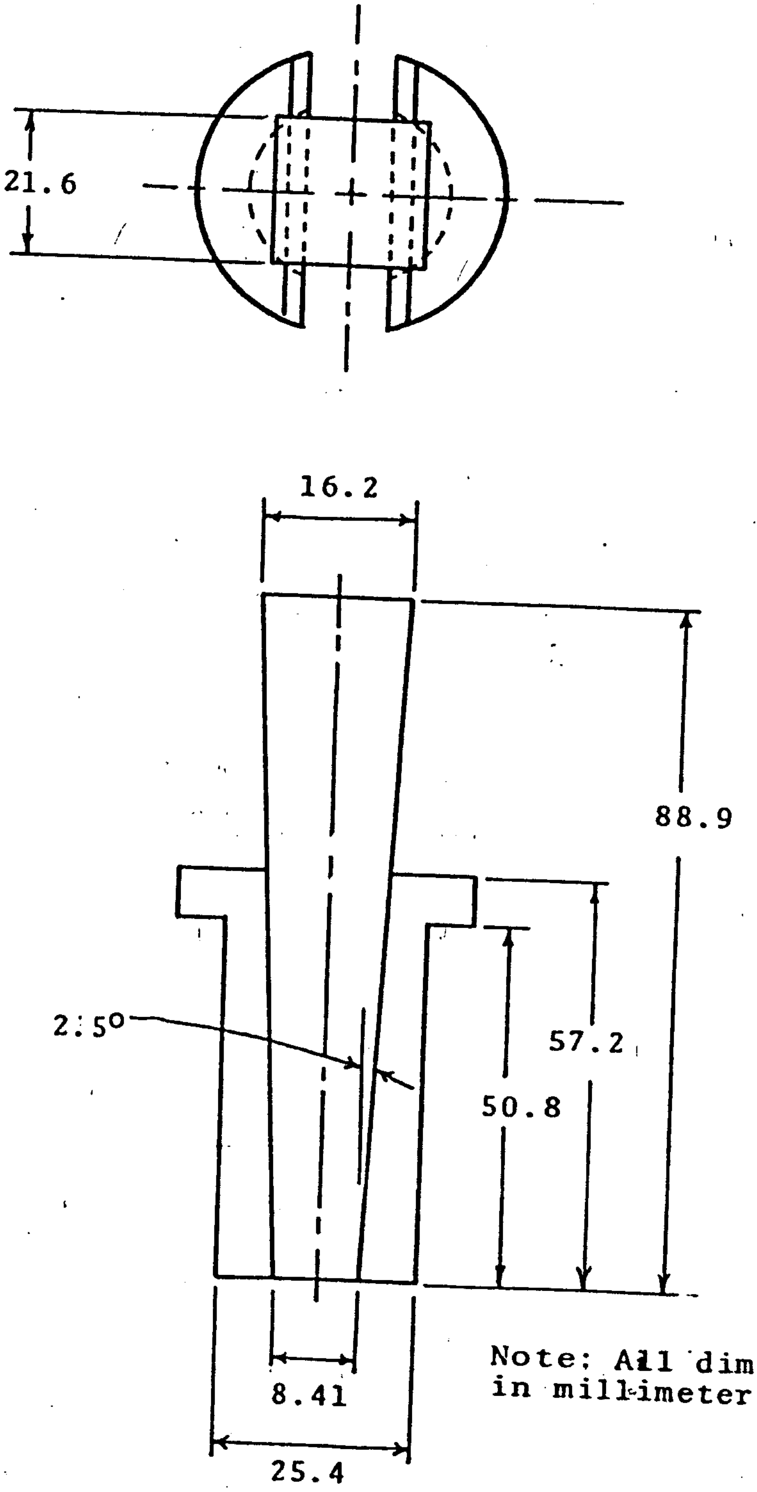


Figure 4 - Test set-up showing recording equipment.



Note: All dimensions in millimeters.

Figure 5 - Three piece wedge assembly.

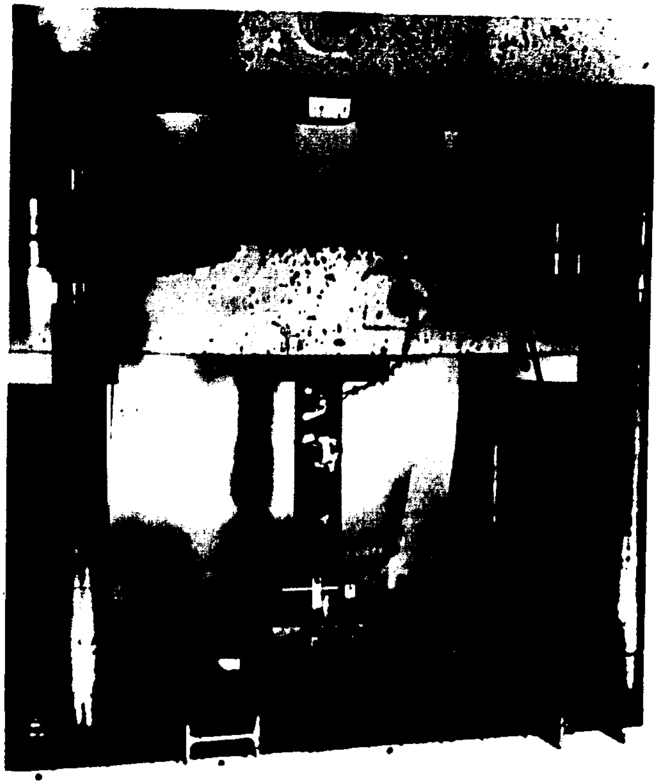


Figure 6 - Test set-up showing loading tup and attached LVDT.

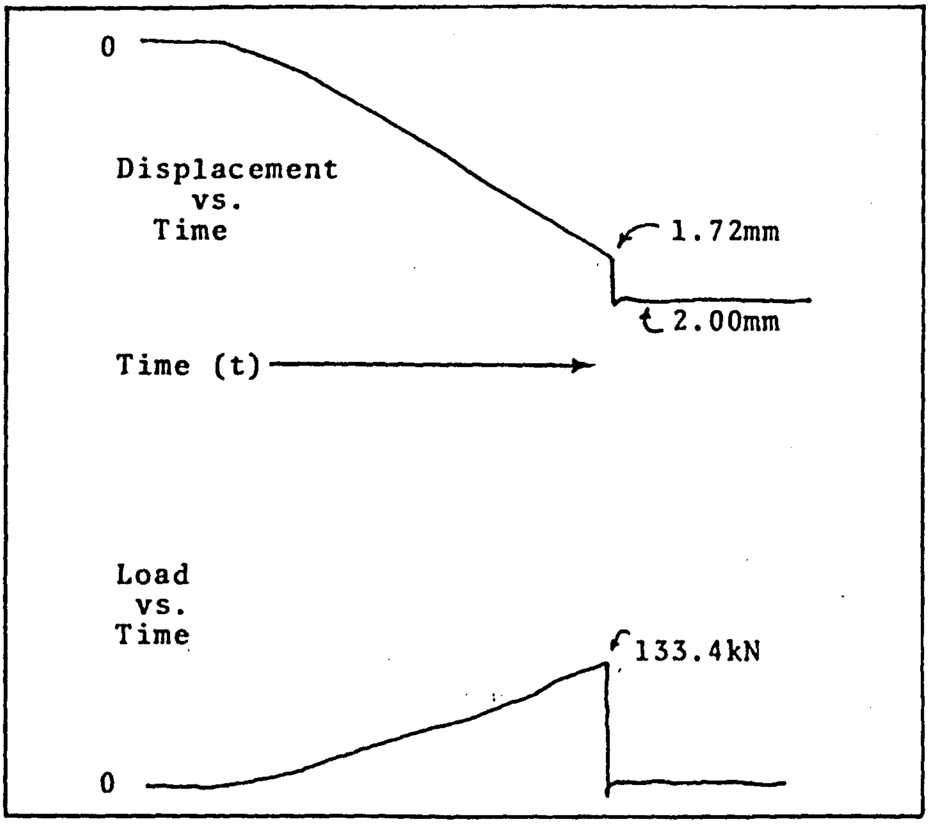


Figure 7 - Typical plot showing load vs. time and displacement vs. time.

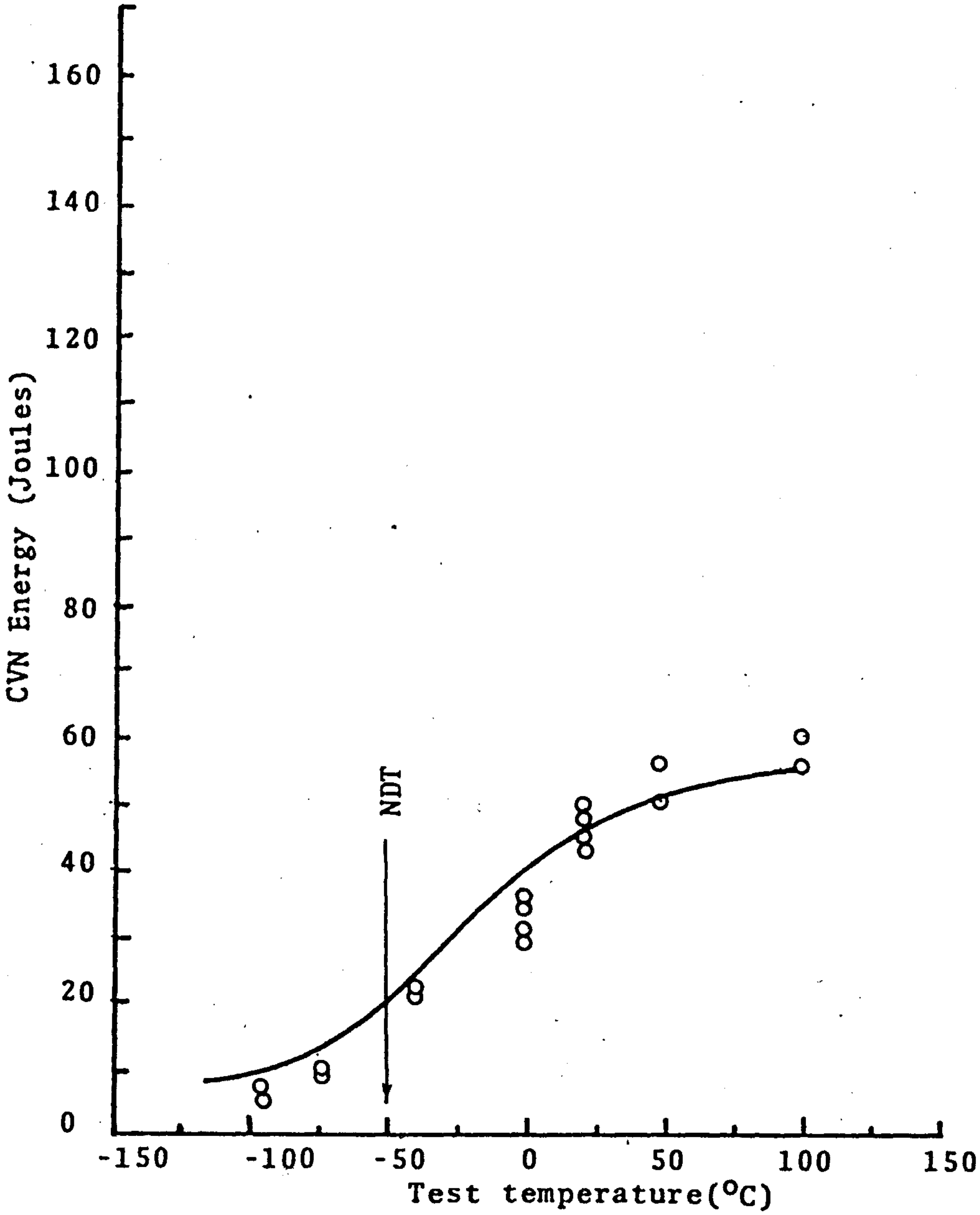


Figure 8 - CVN Results (A514-50.8mm)

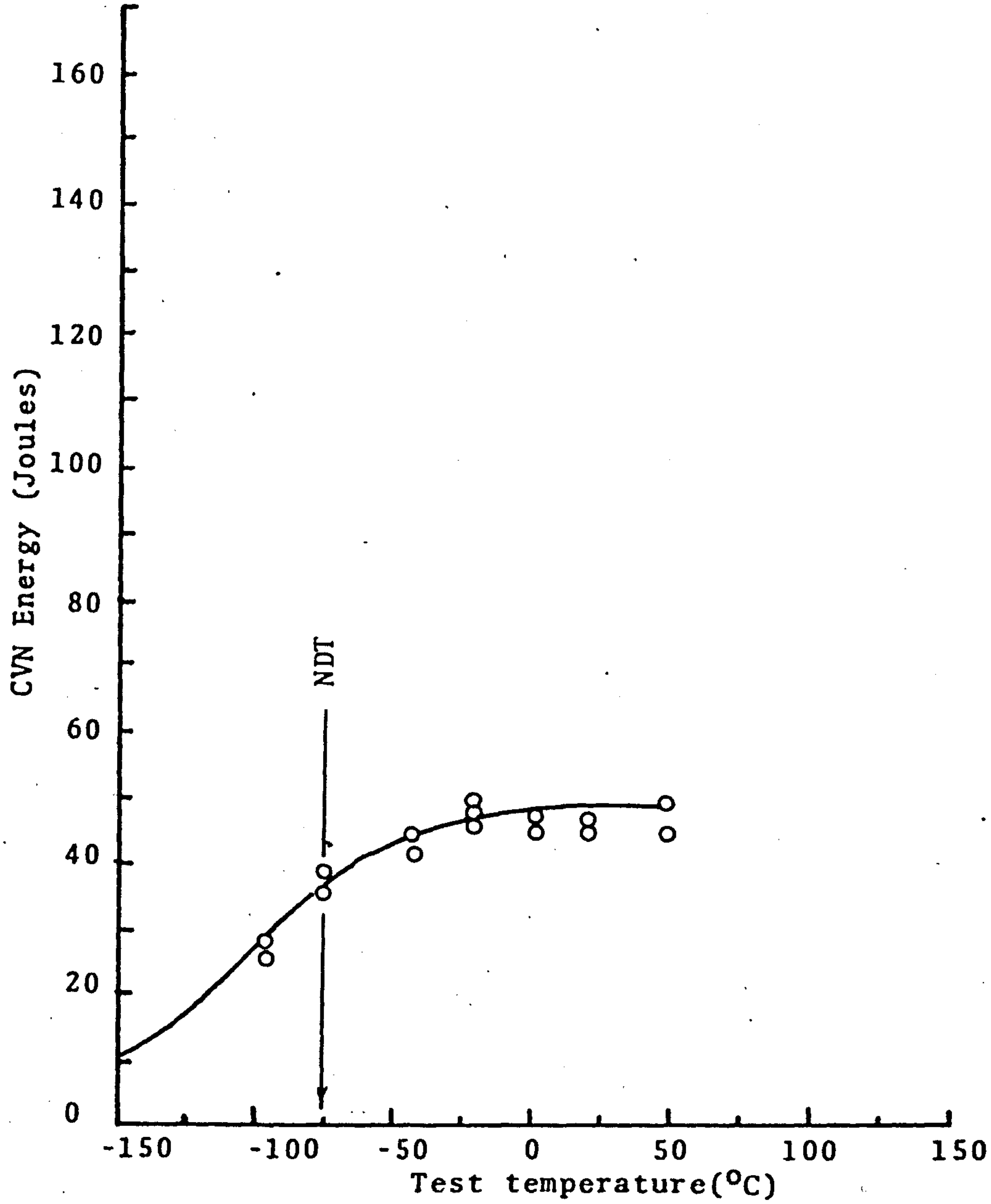


Figure 9- CVN Results (A514-25.4mm)

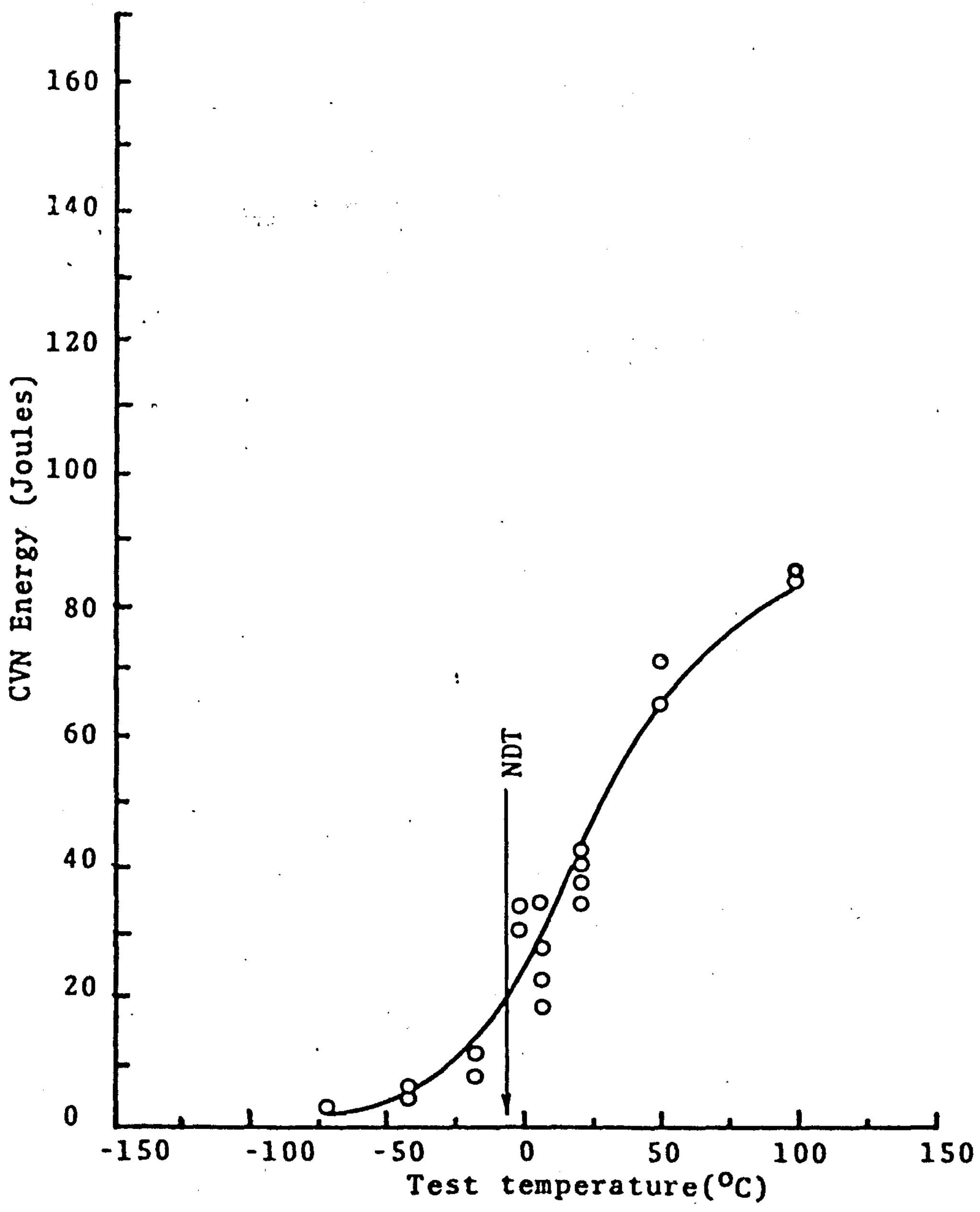


Figure 10- CVN Results (A36-50.8mm)

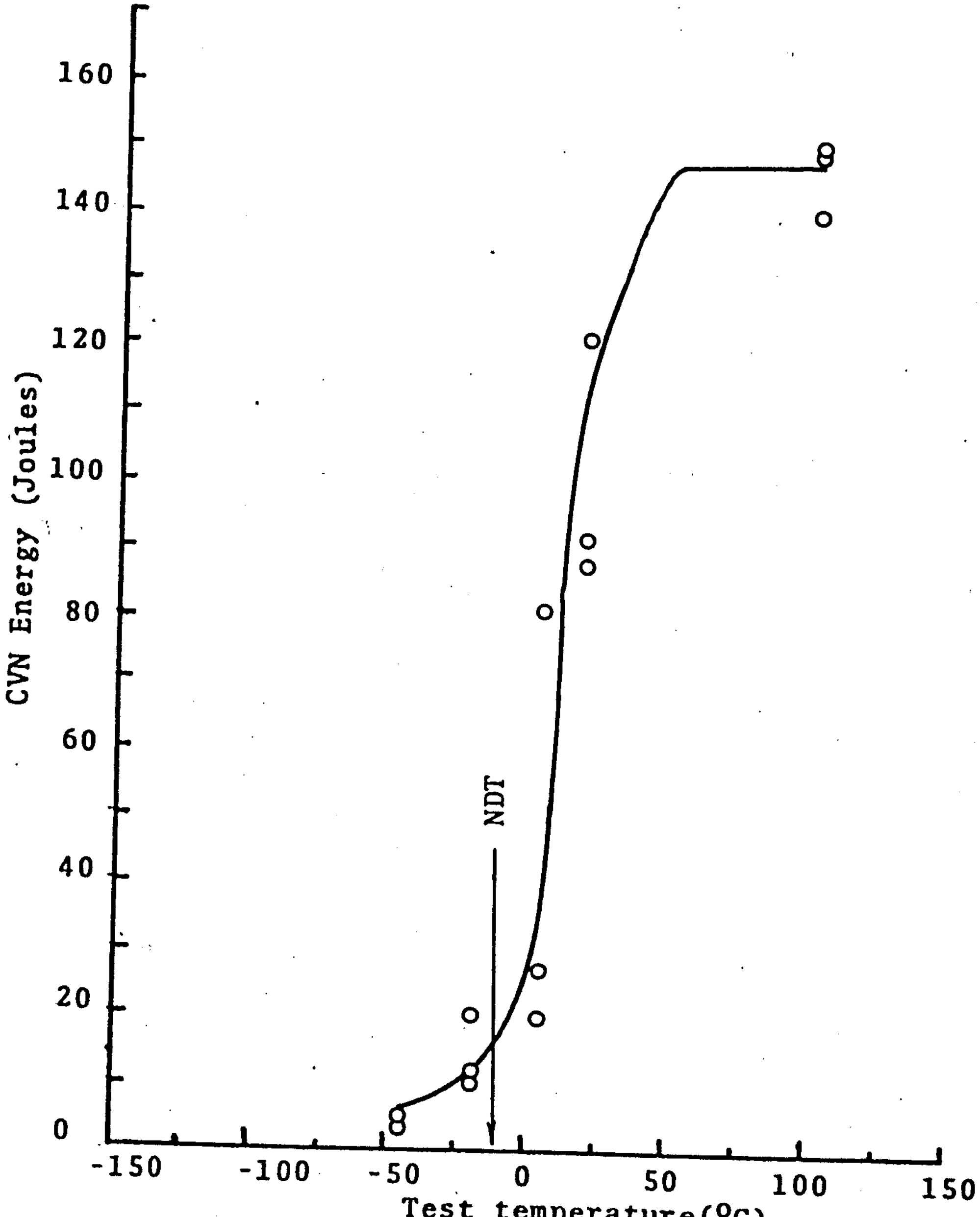


Figure 11- CVN Results (A36-25.4mm)

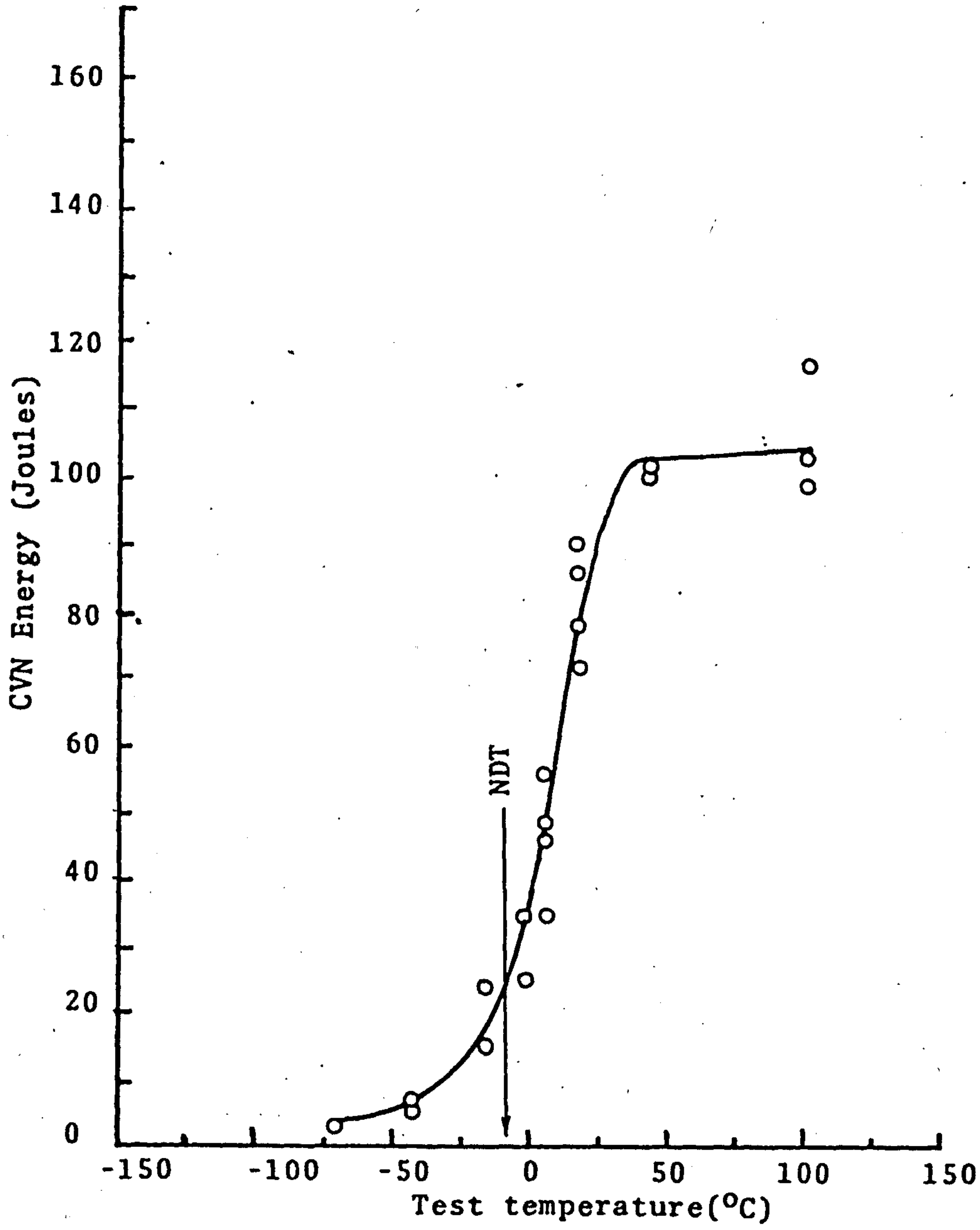


Figure 12 CVN Results (A588-50.8mm)

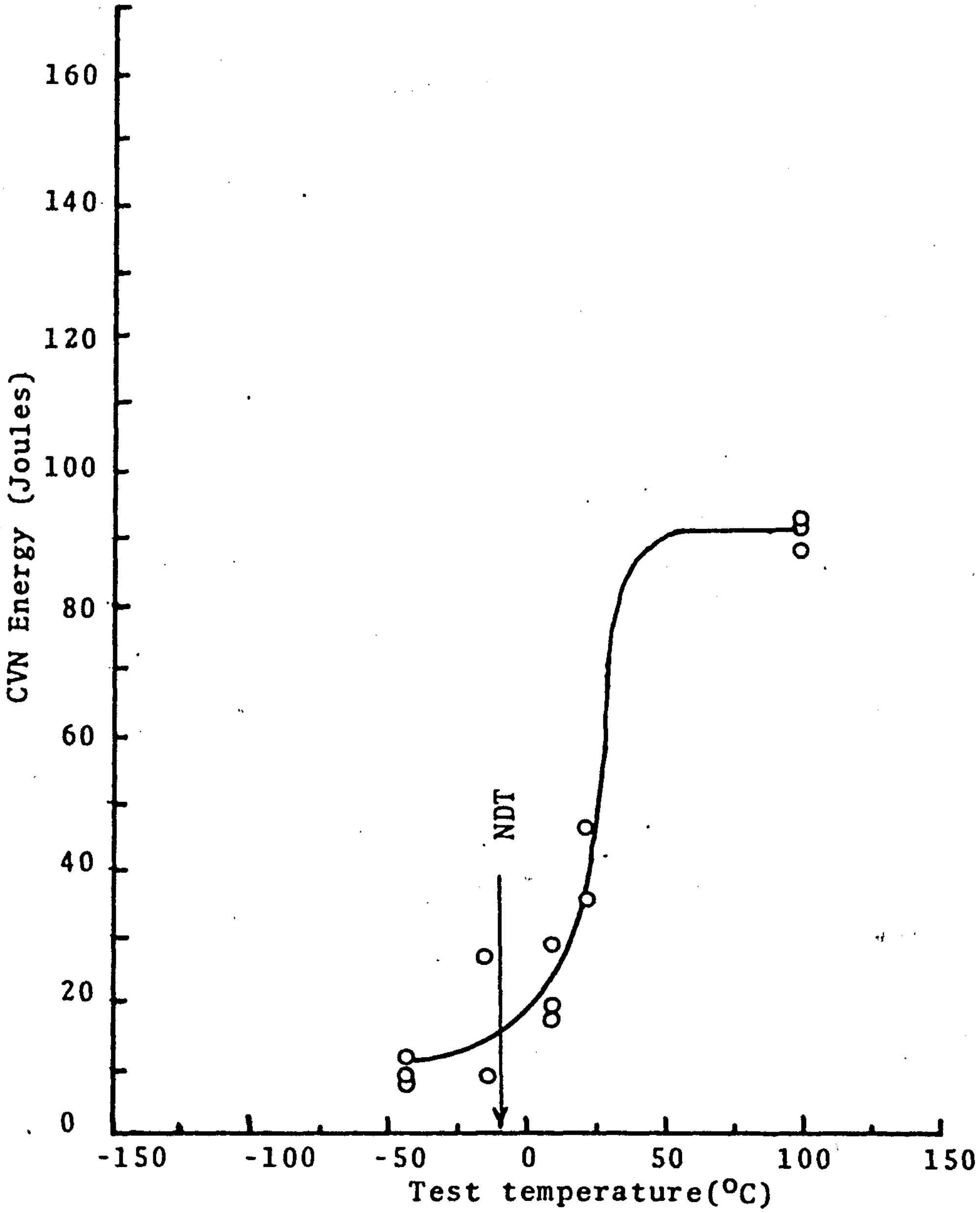


Figure 13- CVN Results (A588-25.4mm)

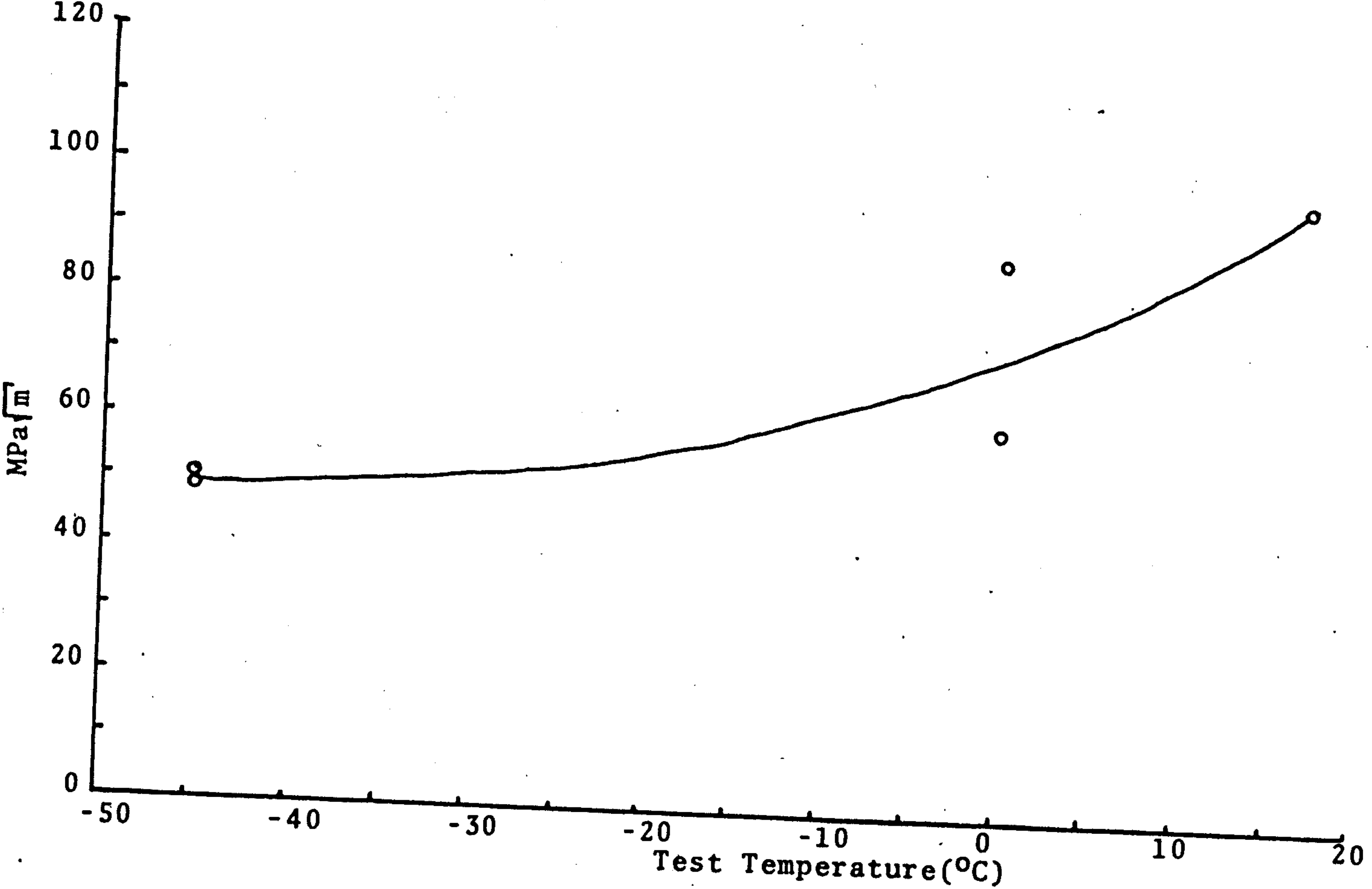


Figure 14 - K_{Ia} vs. temperature (A36-25.4mm)

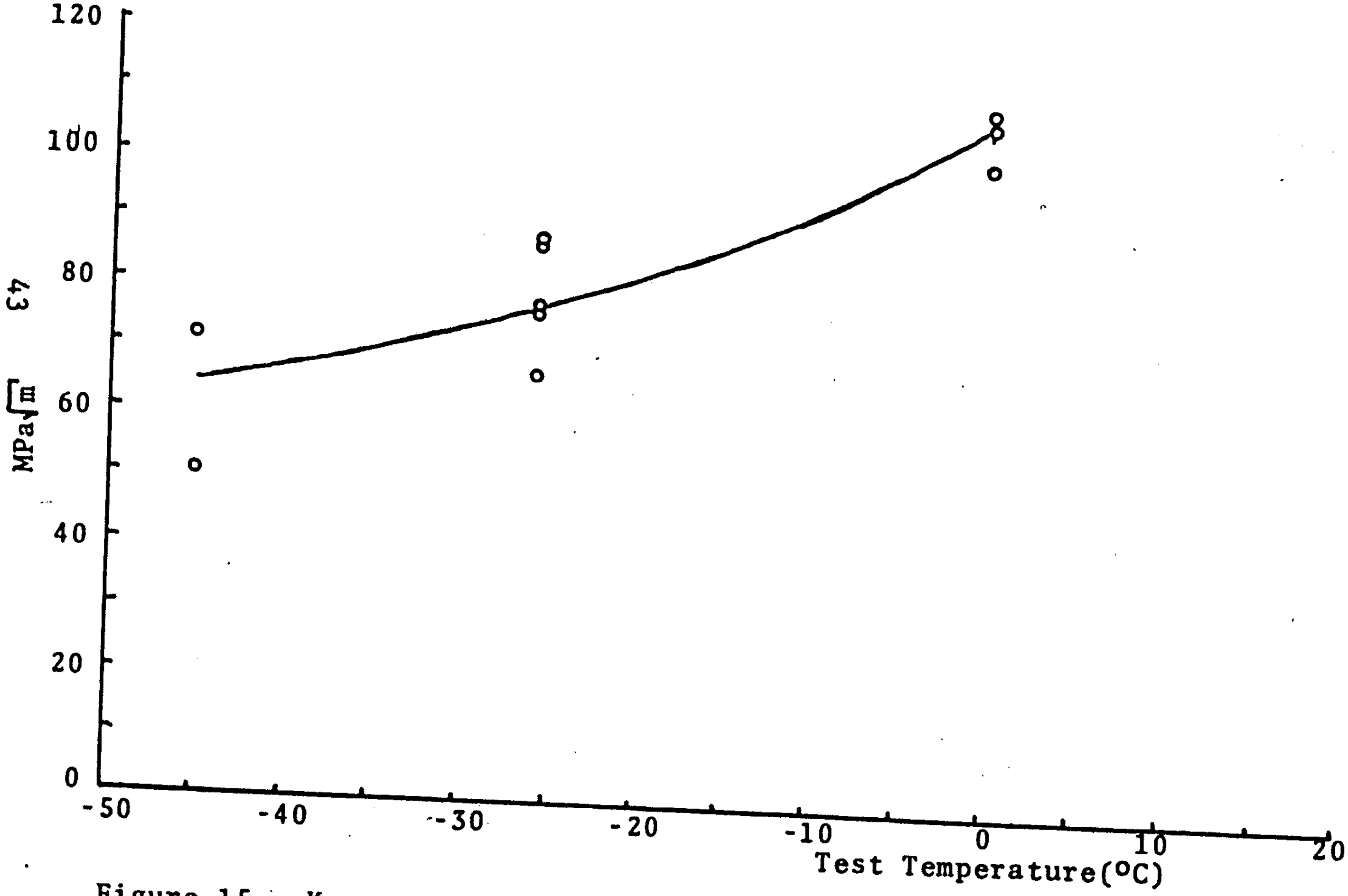


Figure 15 - K_{Ia} vs. temperature (A36-50.8mm)

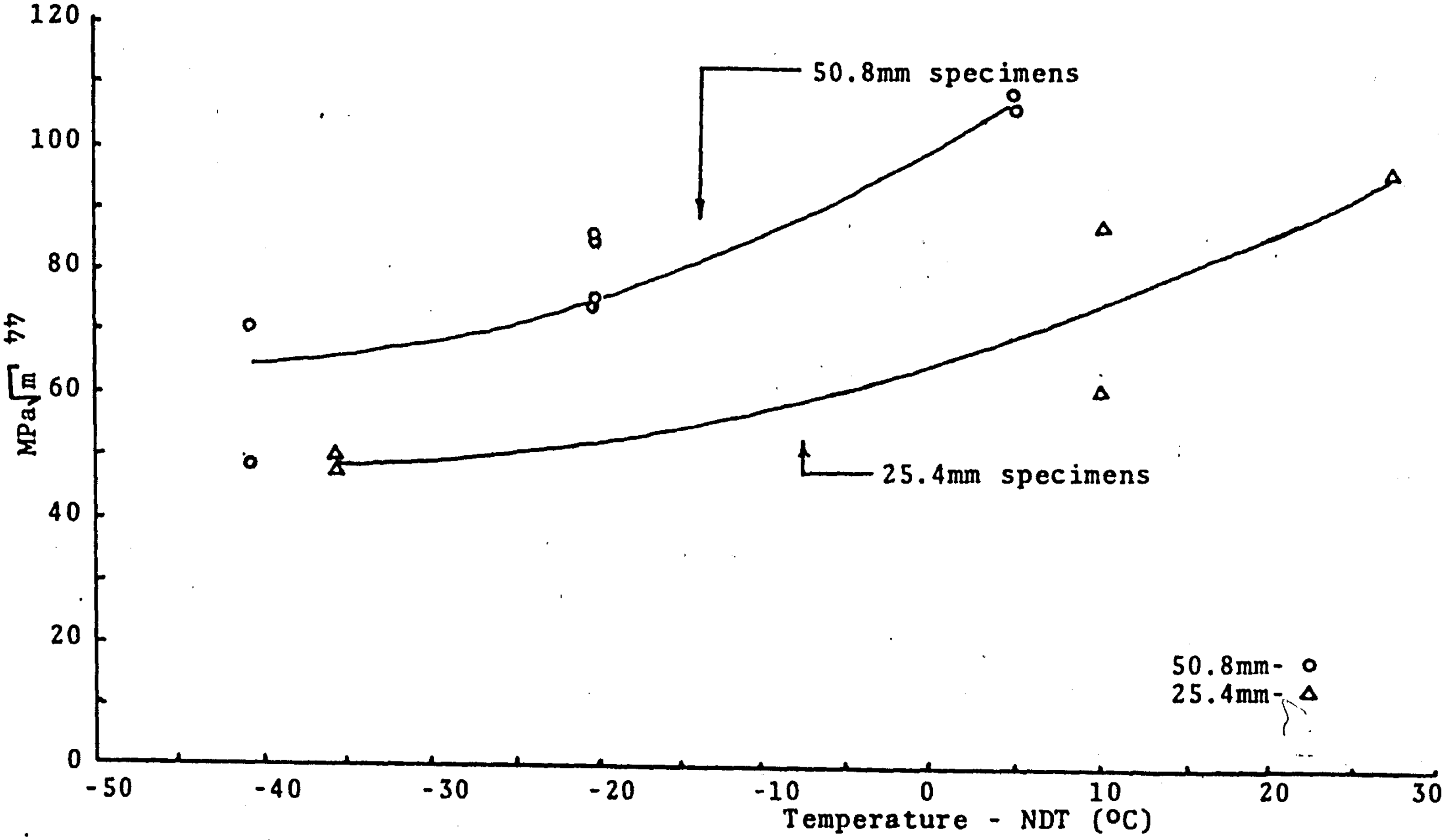


Figure 16 - K_{Ia} referenced to NDT (A36 data)

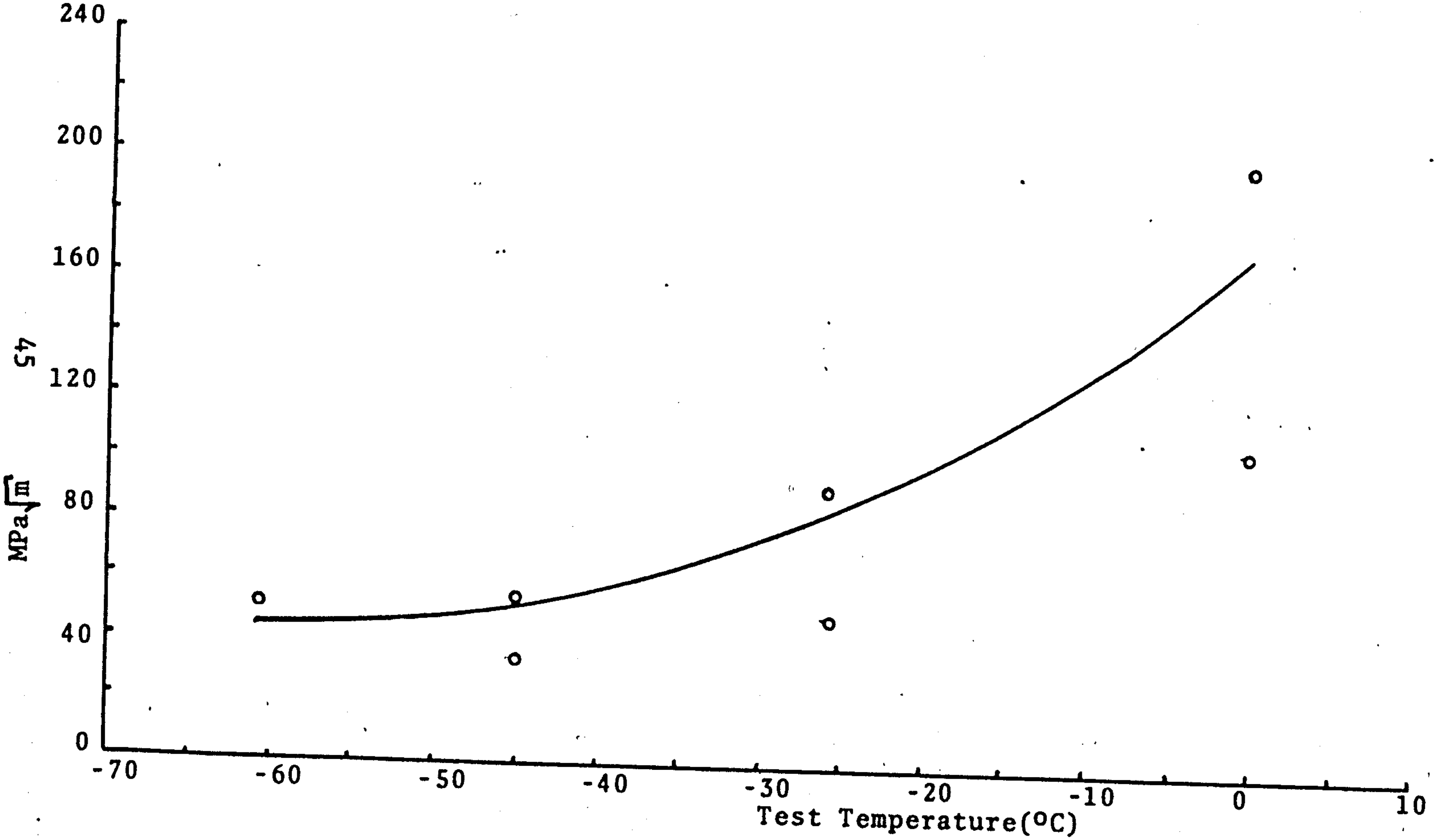


Figure 17 - K_{Ia} vs. temperature (A514-25.4mm)

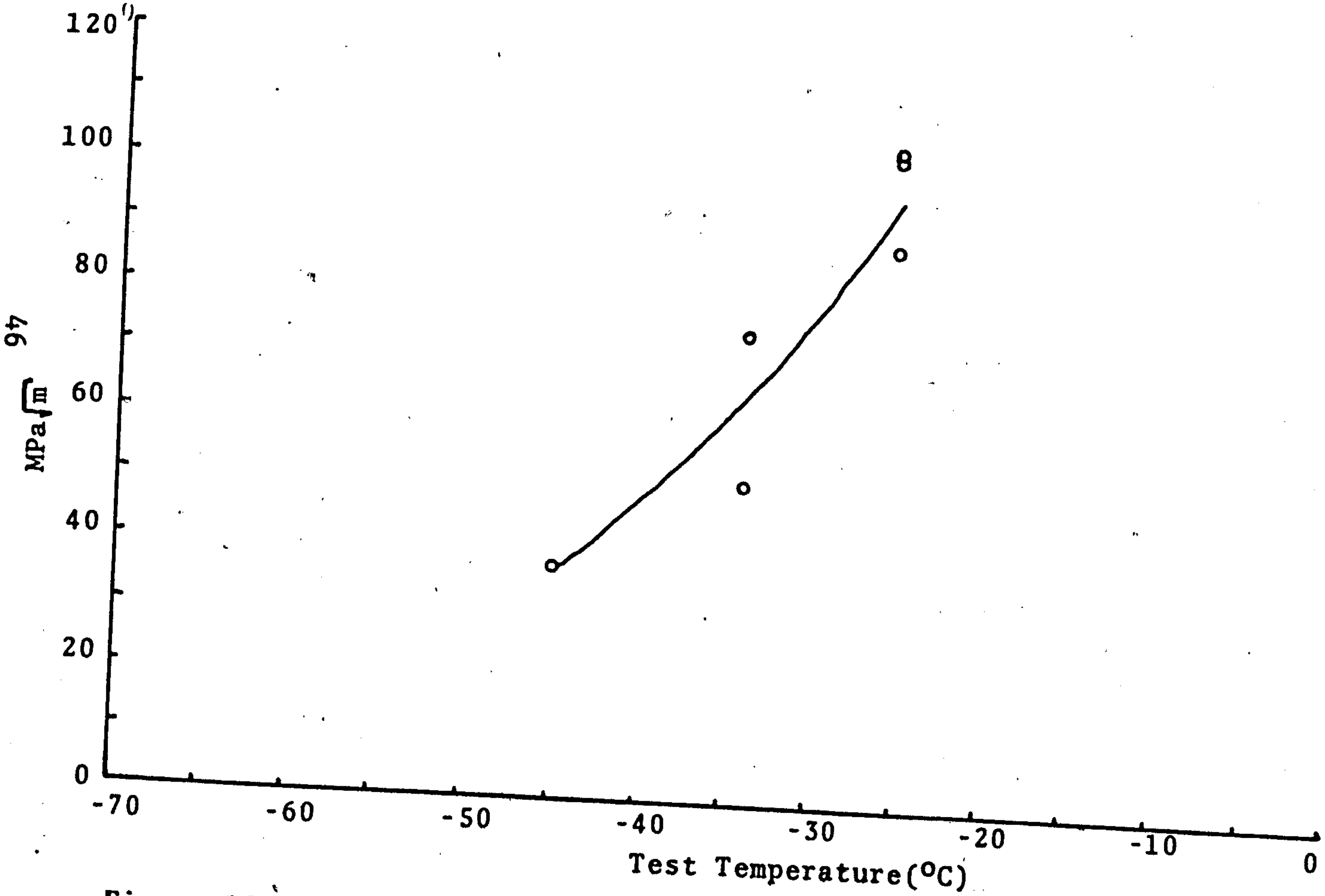


Figure 18 - K_{Ia} vs. temperature (A514- 50.8mm)

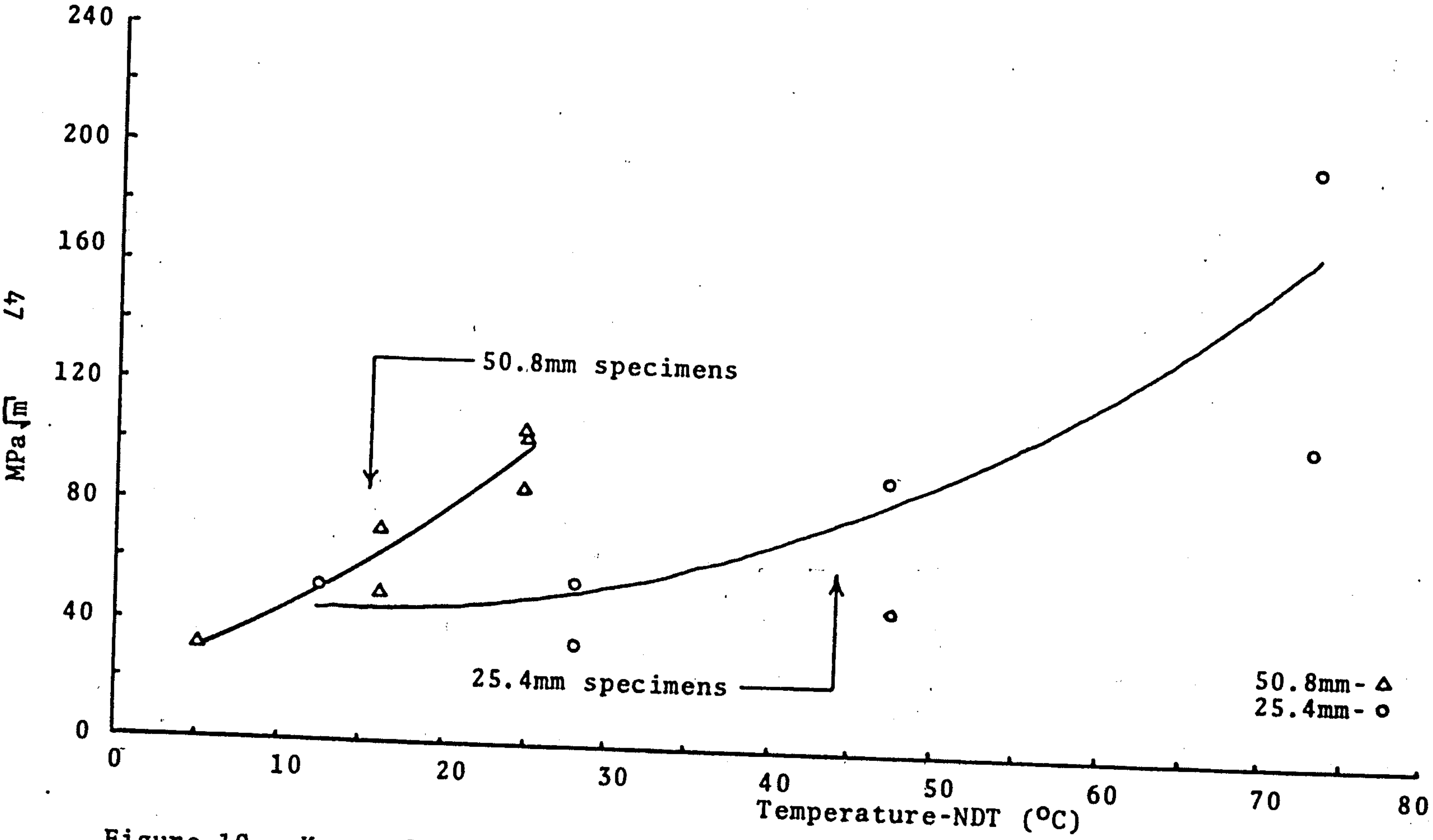


Figure 19 - K_{Ia} referenced to NDT (A514 data)

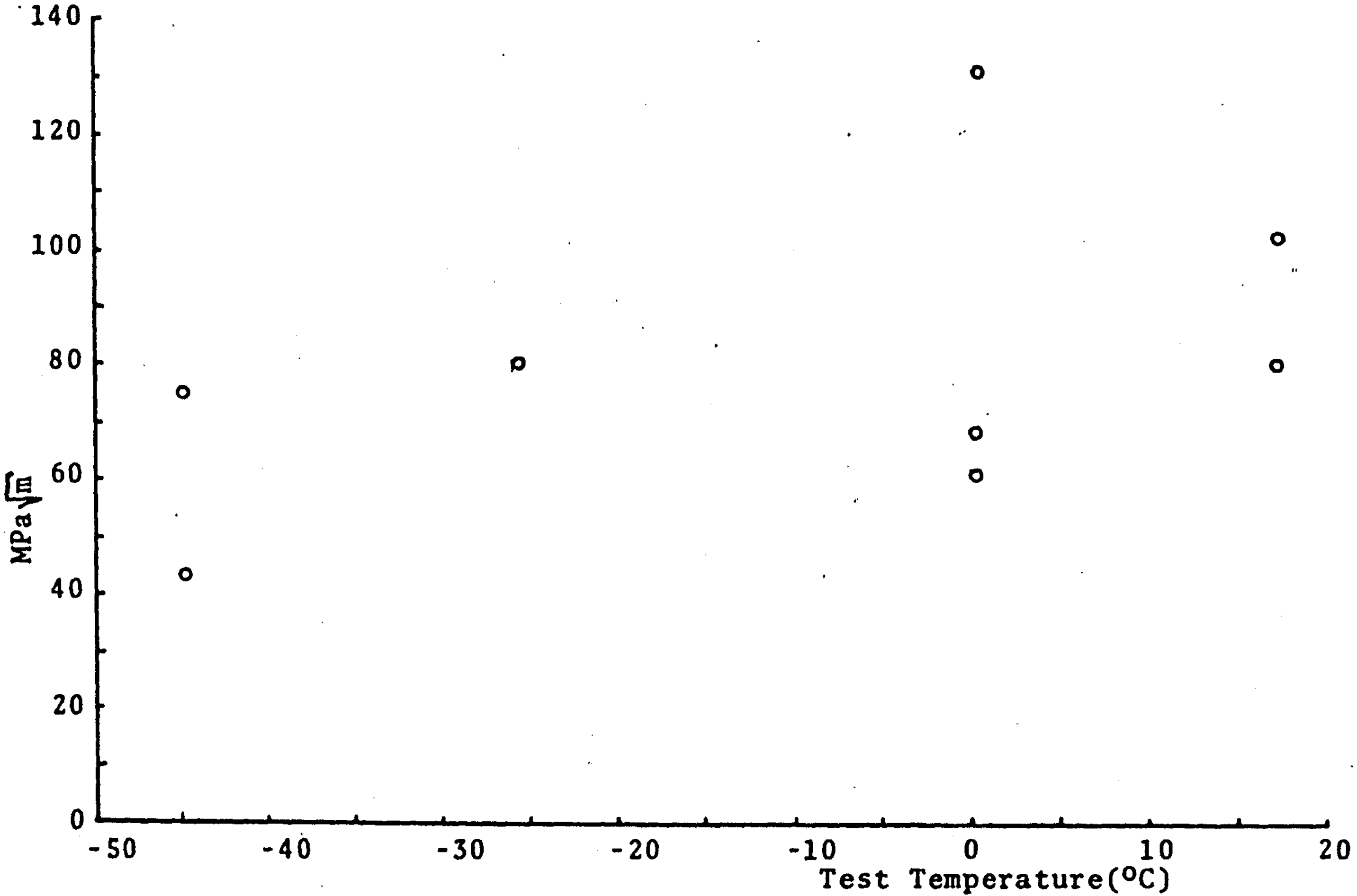


Figure 20 - K_{Ia} vs. temperature (A588-25.4mm)

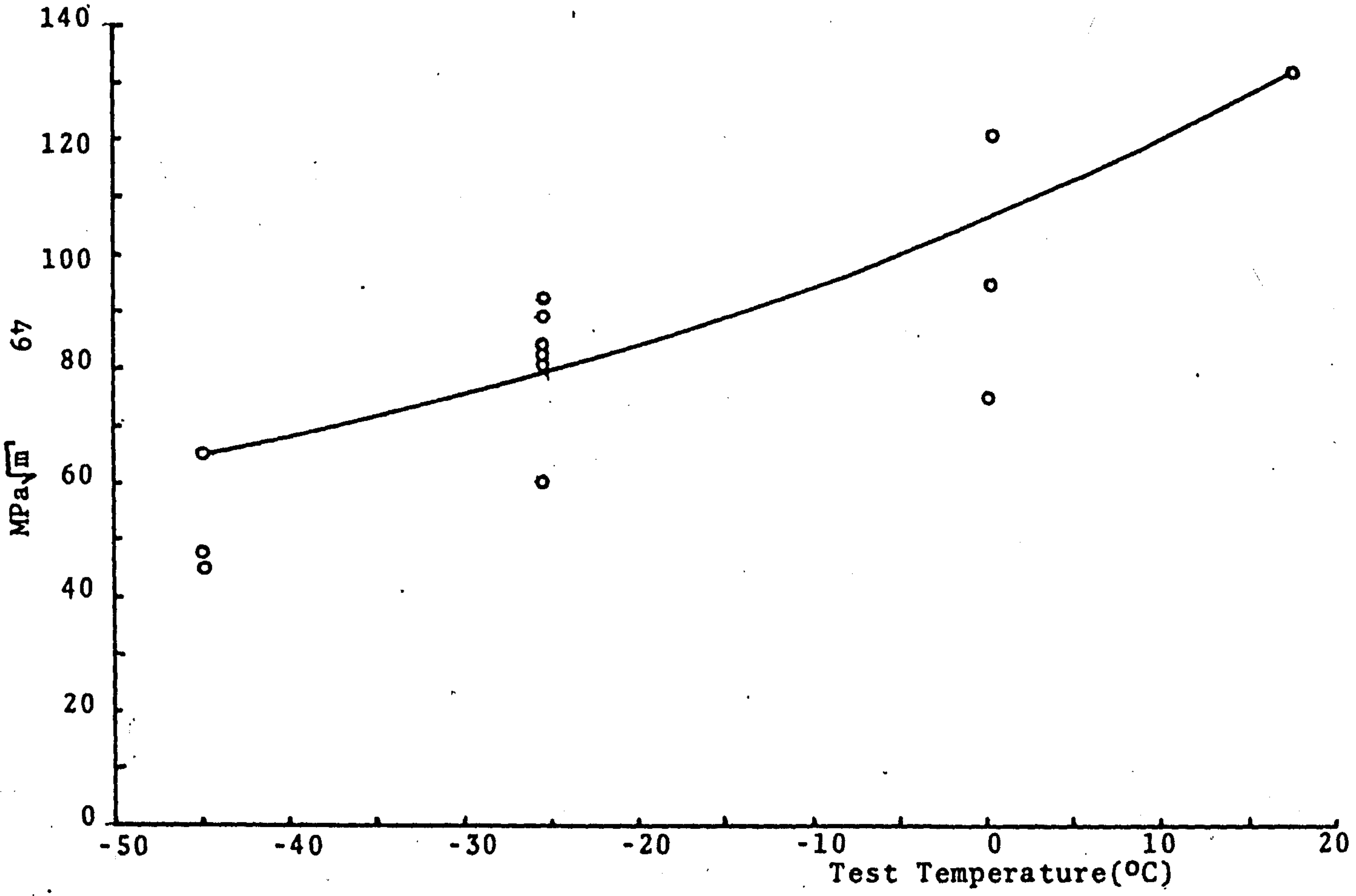


Figure 21 - K_{Ia} vs. temperature (A588-50.8mm)

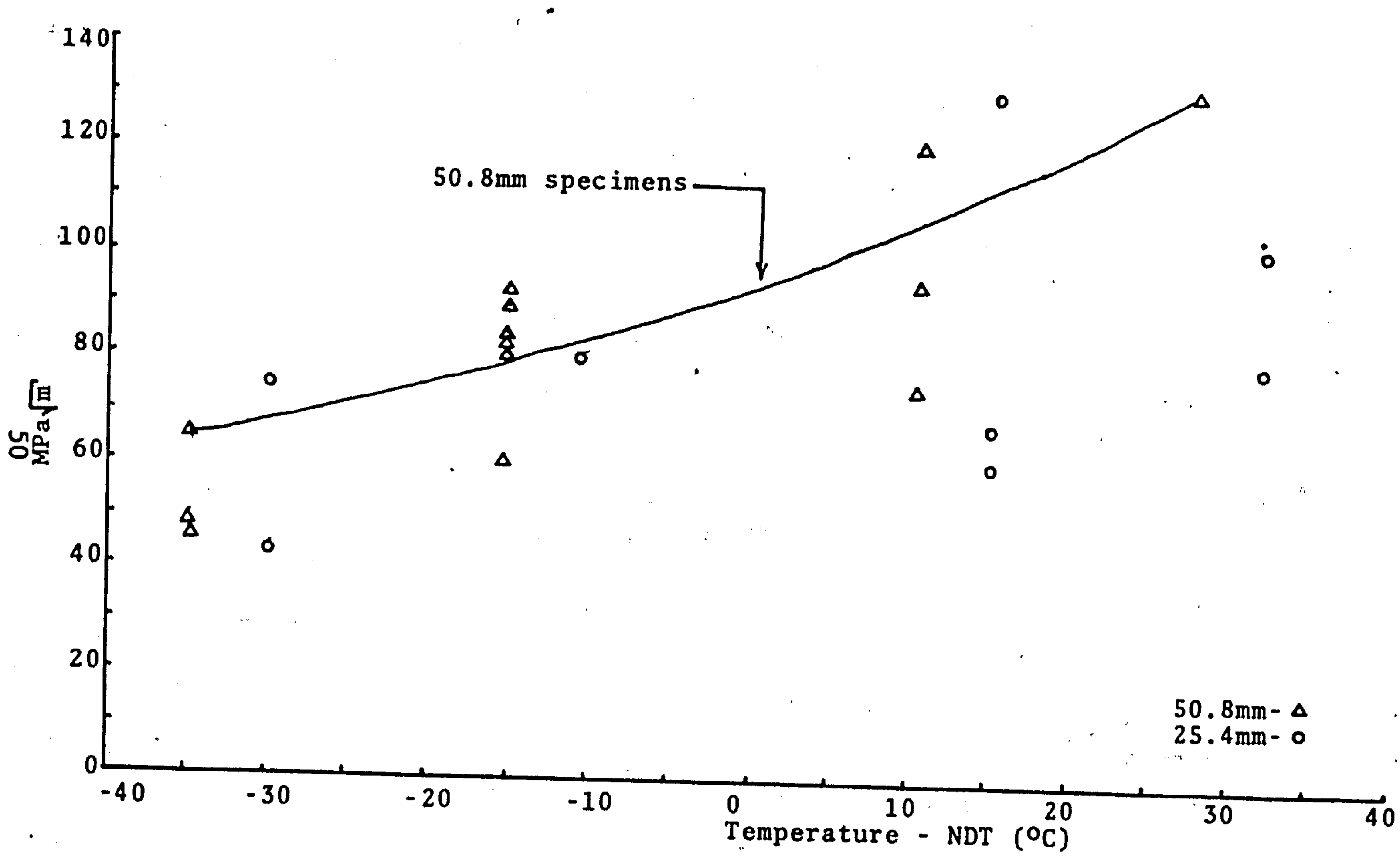


Figure 22 - K_{Ia} referenced to NDT (A588 data)

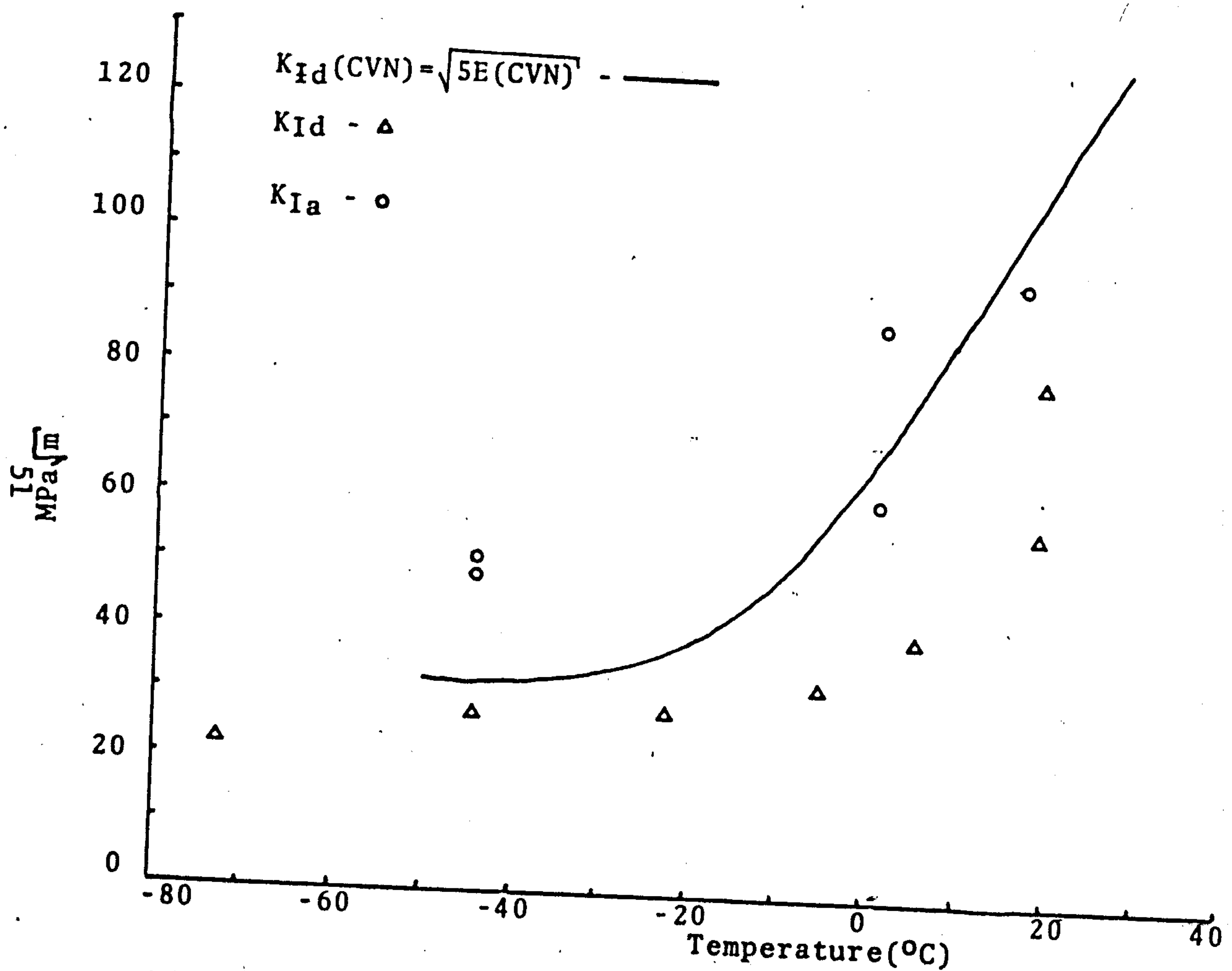


Figure 23 - Comparison of K_{Ia}, K_{Id}, and $K_{Id}(CVN)$ (A36-25.4mm)

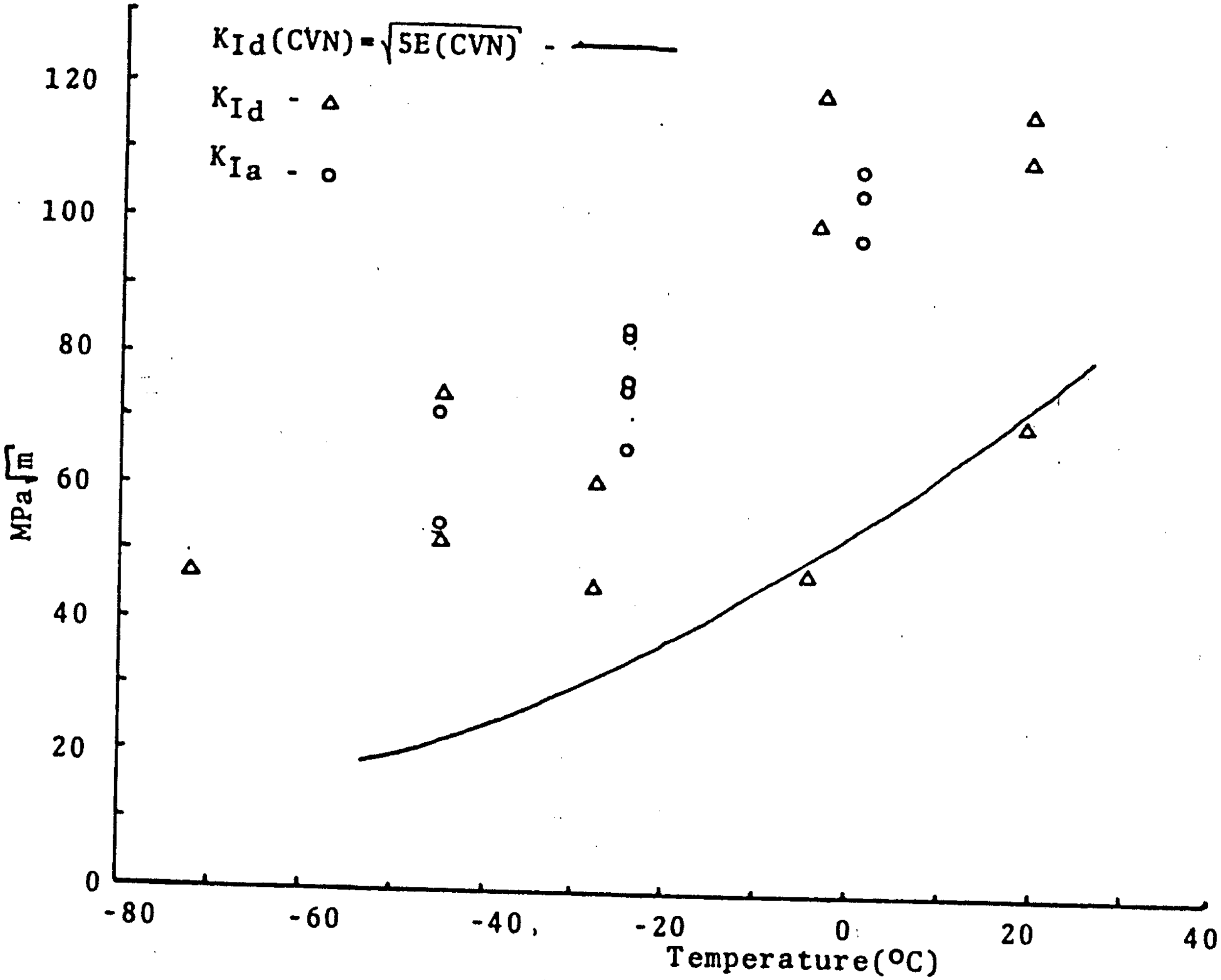


Figure 24 - Comparison of K_{Ia}, K_{Id}, and $K_{Id}(CVN)$ (A36-50.8mm)

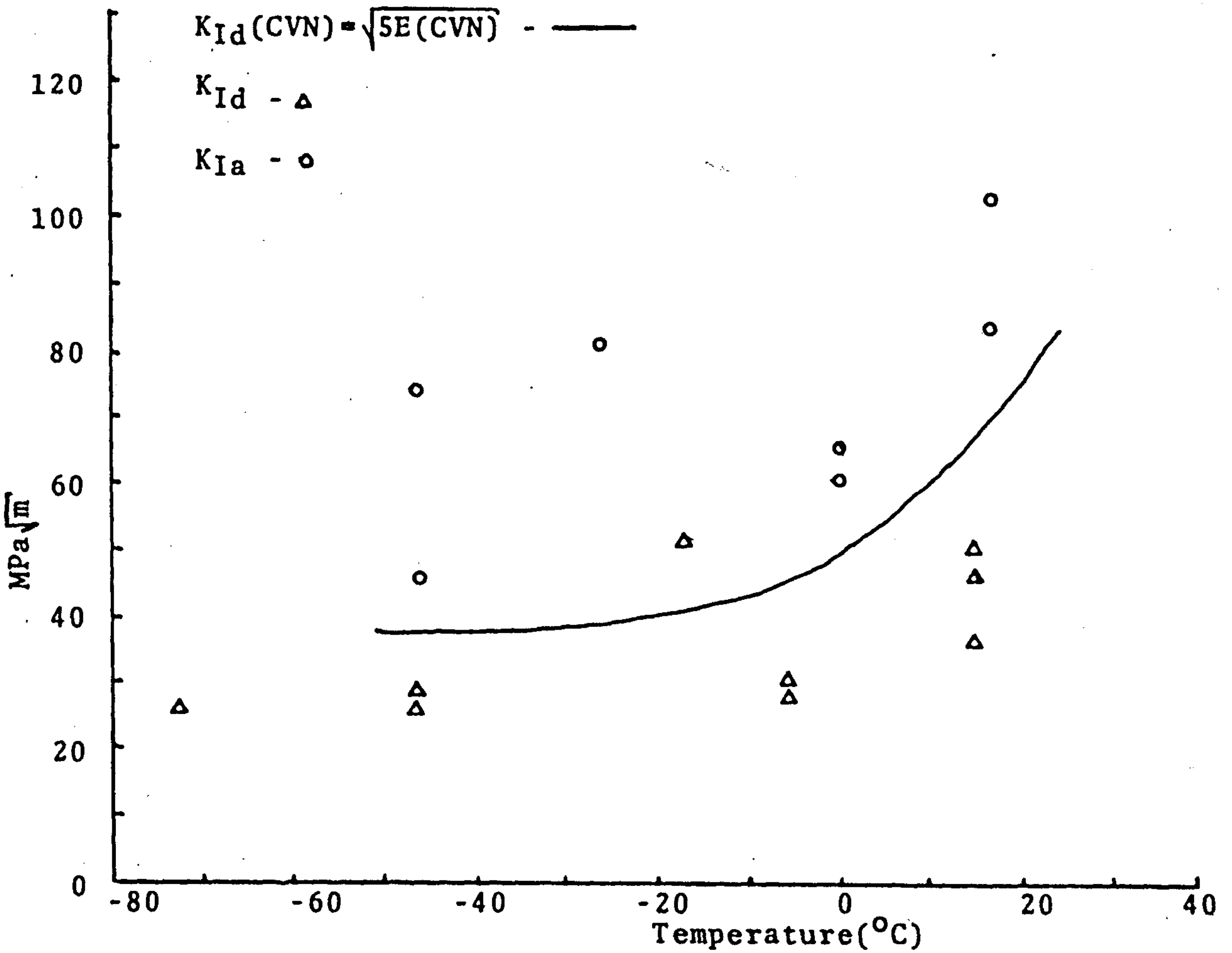


Figure 25 - Comparison of K_{Ia},K_{Id},and $K_{Id}(CVN)$ (A588-25.4mm)

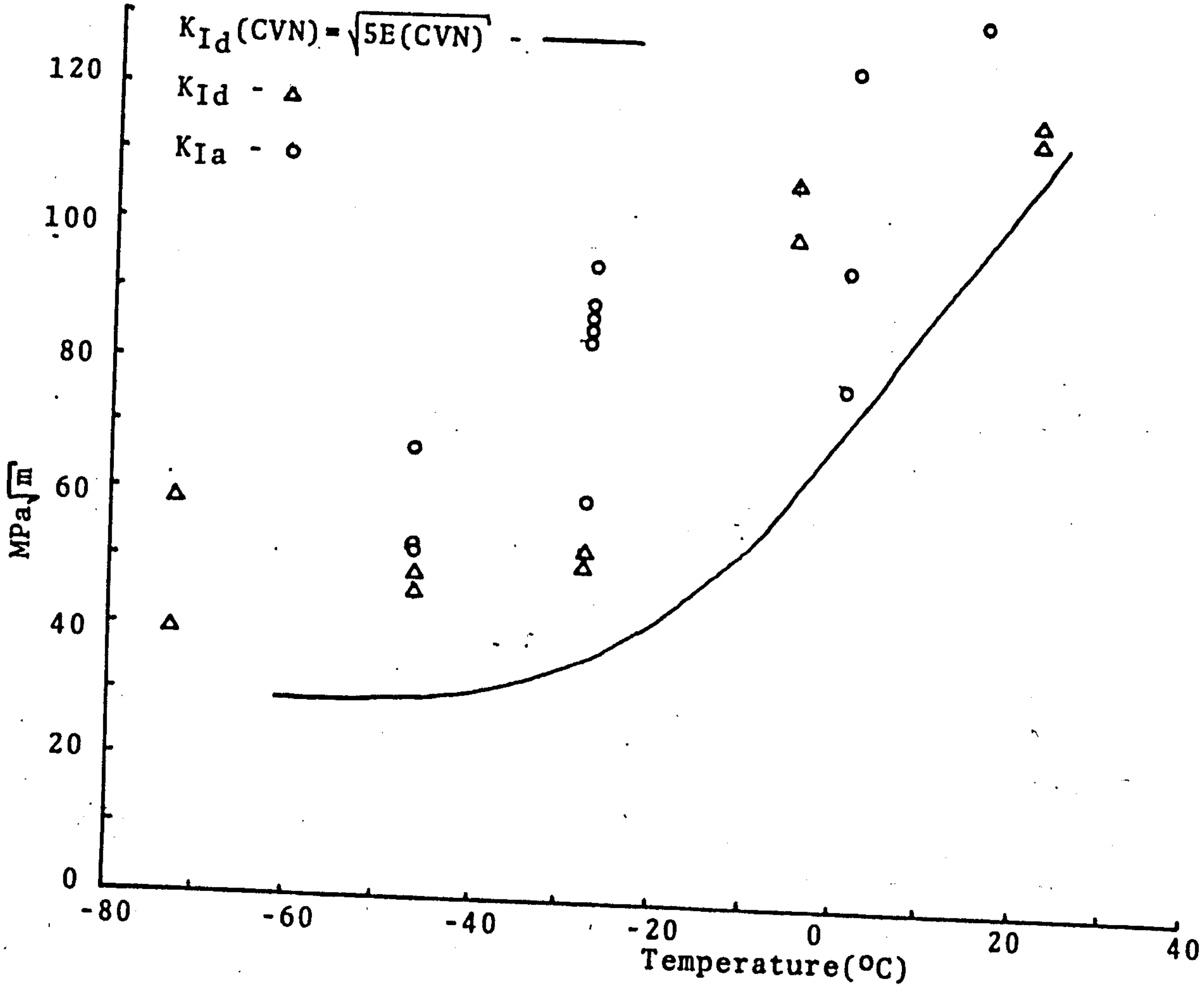


Figure 26 - Comparison of K_{Ia},K_{Id},and $K_{Id}(CVN)$ (A588-50.8mm)

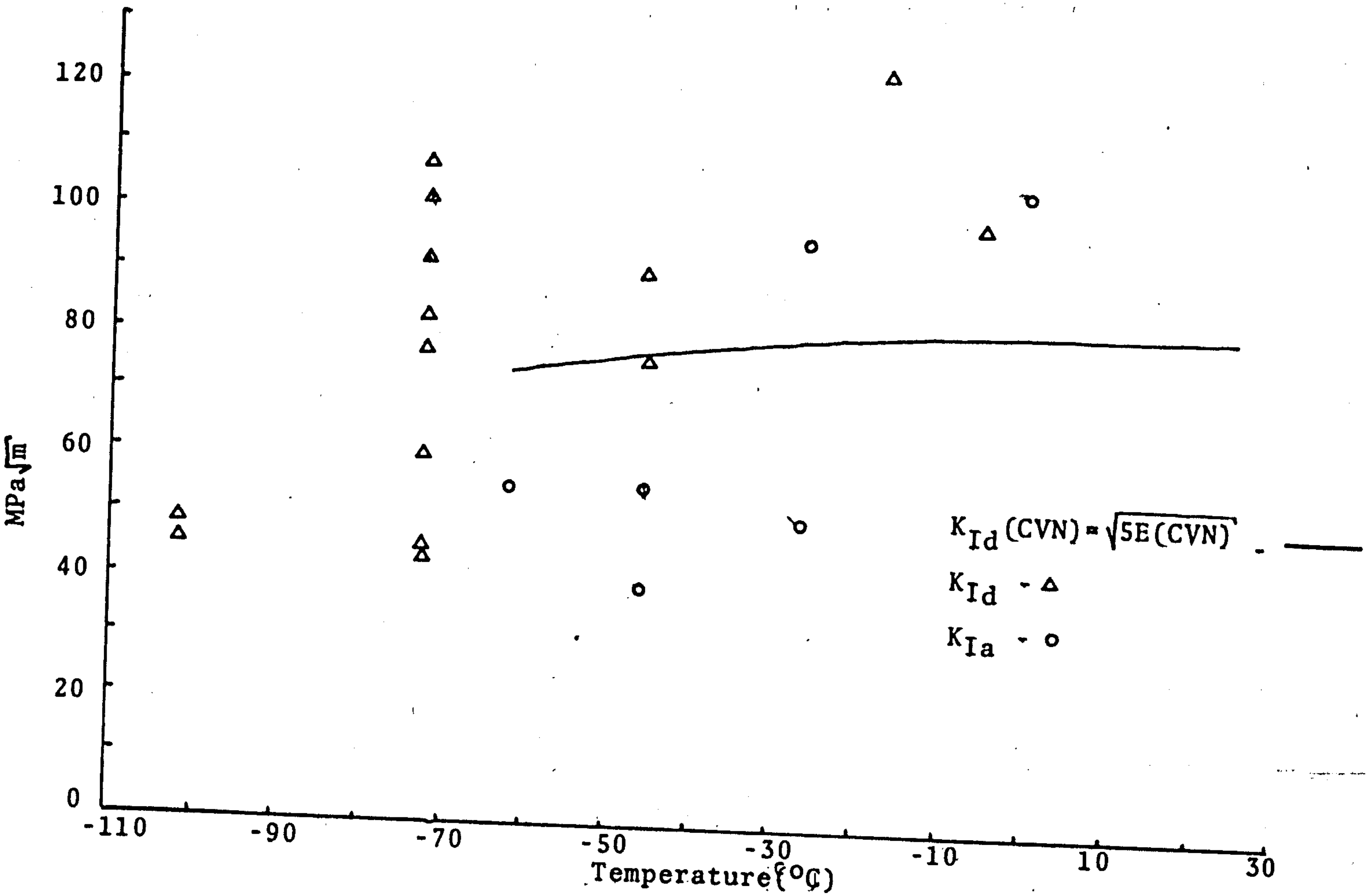


Figure 27 - Comparison of K_{Ia}, K_{Id}, and K_{Id}(CVN) (A514-25.4mm)

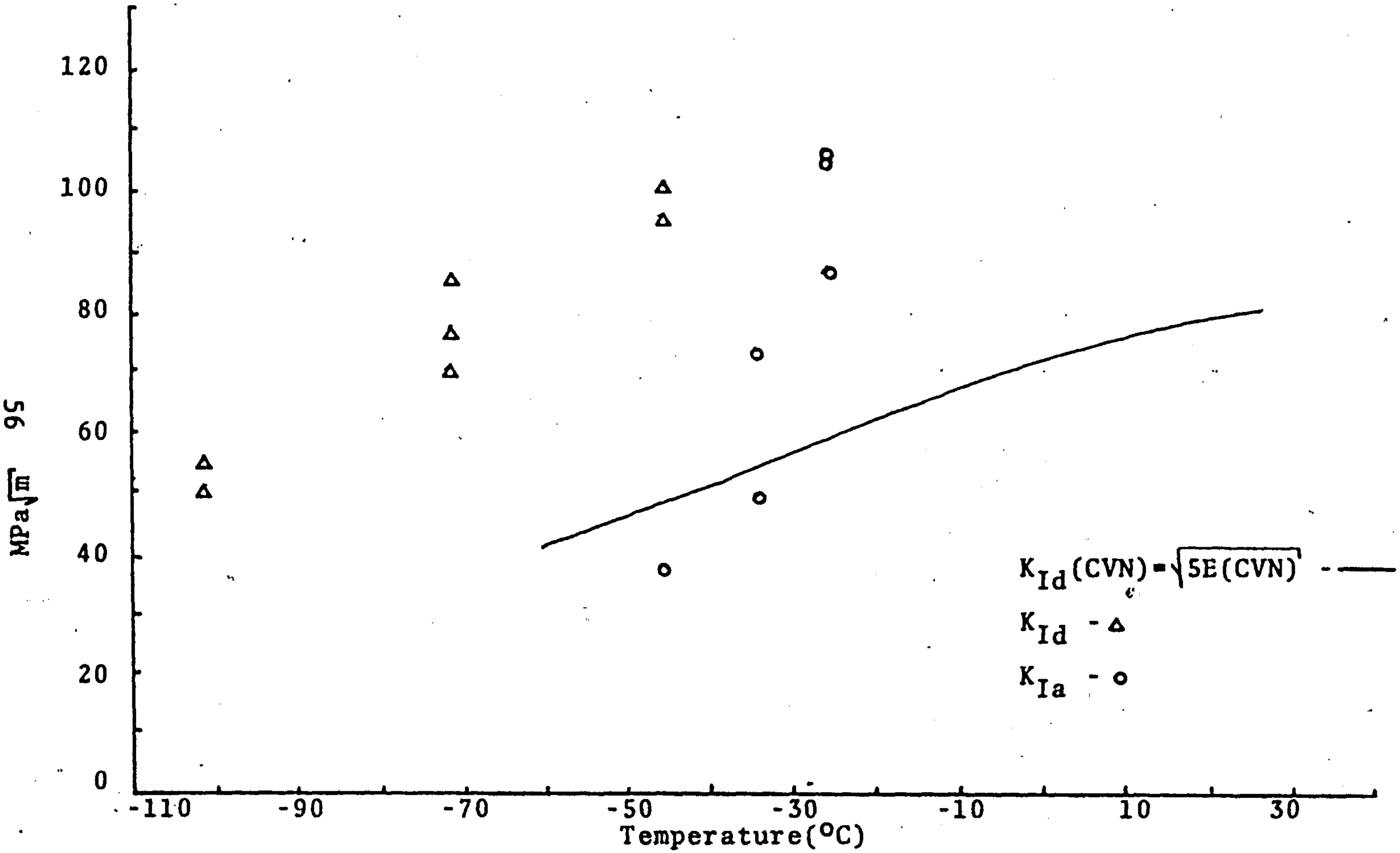


Figure 28 - Comparison of K_{Ia}, K_{Id}, and $K_{Id}(CVN)$ (A514-50.8mm)

VITA

Mark C. Durkee was born in Neubrucke, Germany, on January 11, 1957, to Carol and Frank P. Durkee. He attended Trenton State College from 1976 to 1980 and graduated with a B.S. in Mechanical Engineering and a minor in mathematics.