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A fracture toughness analysis of a533 Grade B Class 1 and Class 2 plate for pressure vessel service.

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A FRACTURE TOUGHNESS ANALYSIS OF A533 GRADE B CLASS 1 AND CLASS 2 PLATE FOR PRESSURE VESSEL SERVICE

by

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ABSTRACT

A mechanical property analysis was conducted of A533 Grade B Class 1 and Class 2 plate materials. The thrust of experimentation was fracture toughness determination over a range of temperatures. To complement this information, an involved investigation of various other mechanical and microstructural properties was completed.

J-integral analysis was used in the present study. Several J techniques were employed although data and calculations were done on data obtained by one procedure: determination of crack growth by visual measurement.

Class 2 material proved to be as tough as Class 1 material by both Charpy Impact toughness and fracture toughness investigations. In Class 1 material, toughness increased with increasing temperature up to a shelf of 232 MPa$\sqrt{m}$ (211 Ksi$\sqrt{in}$) at room temperature. Class 2 material showed a 240 MPa$\sqrt{m}$ (224 Ksi$\sqrt{in}$) shelf at ambient temperatures and above. The toughness criteria used for testing was the K_{IR} curve normalized to the NDT temperature. In both cases toughness fell below the nominal K_{IR} curve at 100°C (212°F). However, at the other temperatures tested, both materials passed the K_{IR} criterion by a margin.

INTRODUCTION

Within the last five years a number of new high strength materials have become candidates for use in thick walled pressure vessels. The Heavy Sections Steel Technology Program and Industry Cooperative Program have done a great deal to characterize many of the steels now in such use, however, technological advances have brought about higher strength materials and thus created the need for documentation of the toughness of these materials. For example, past studies have investigated toughness characteristics of A533 Grade B Class 1 plate. Since toughness cannot reliably be related to the strength level of a material, any modification of the chemistry or heat treatment which alters strength, may also alter the toughness. Due to the interest in some of the higher strength versions of present materials and more specifically the higher strength level material A533 Grade B Class 2, an exploratory program was launched to develop strength-toughness relationships over a range of temperatures. The A533 Grade B Class 1 strength level was about 599 MPa (86.9 Ksi) tensile strength and the Class 2 strength level was about 685 MPa (99.4 Ksi).

J-integral analysis was chosen in conducting these fracture toughness characterizations as they were in the other most recent studies done at Lehigh University. No attempt was made to obtain classical K_{IC} data. This enabled the experimenter to save time and conserve materials through the use of 38 mm (1½ inch) compact tension specimens. Recent studies[1] conducted on A508 Class 2 and

Class 4 have successfully utilized J-integral tests. Various possibilities were investigated in this previous study and the best test methods were recommended. With a few refinements, these techniques, have been presently employed.

BACKGROUND

Valid fracture toughness results for pressure vessel studies are difficult to obtain, especially at room temperature and above. Depending upon the tests run, specimen thicknesses required can be 300 mm (12 inches) thick,[2] which is an unreasonable size to work with in most cases. A technique that can utilize smaller sections would be beneficial from the standpoint of experimentation as well as economical in material conservation. Specimens that would otherwise be too small to produce valid K_{IC} tests might none-the-less be used to estimate a toughness value even in cases where plastic deformation at the crack tip and some crack growth prior to fracture are present.

The choice for the present study was to use a J-integral toughness analysis. This method of fracture toughness evaluation fulfilled the desire to use smaller specimens. Rice[3] did initial studies with this technique in 1968. The J-integral can be defined as the averaged strain at the crack tip, or interpreted differently, the energy required for crack extension. A critical value of K can be related to the critical value of J, (J_{IC}), and therefore provide an understandable fracture criterion. With J related to the energy available for crack extension, G, it can be related by the following equations:

$$K^2 = \frac{E}{1 - \nu} G \qquad \text{(plain strain)} \qquad (1)$$

$$K^2 = EG \qquad \text{(plain stress)} \qquad (2)$$

$$K = \sqrt{\frac{JE}{1 - \nu^2}} \qquad (3)$$

Here K is the stress intensity, G, the strain energy release rate, ν is Poisson's ratio, and E is Young's modulus.

Determination of J_{IC}

The J-integral can be interpreted as the potential energy difference between identically loaded configurations of cracked material having neighboring crack sizes of a and a + da. Figure 1a shows this schematically and it can be written

$$J = \frac{- \partial (U/B)}{\partial a} \qquad (4)$$

where U/B is the potential energy described by the area under the load-load point deflection curve, normalized per unit thickness (B). Computation of J_{IC} is shown in Figures 1b - 1d. Figure 1b provides load versus load line displacement data which is utilized to construct a family of U/B versus a curves as shown in Figure 1c. J versus Δ (load point deflection) curves are constructed by evaluating the slopes of each curve in Figure 1c. To determine the critical J values (J_{IC}), Figure 1d will be entered at the critical displacement (Δ_c) and J_{IC} may be thus determined. A minimum of 3 to 4 specimens is needed for such an analysis, and substantial possible error expected with this minimum number.

The present program has again attempted to save on testing costs by using a single specimen approach. Rice et al.[4] have made possible such an approach by developing an expression for J using a single deeply notched (a/w > .6) bend type specimen.

$$J = \frac{2A}{bB} \tag{5}$$

where A is the area under the load-load line displacement curve up to the displacement of interest, B is the specimen thickness, and b is the length of the uncracked ligament. A deeply cracked specimen insures that plasticity is confined to the uncracked ligament. Thus J_{IC} can be determined from the load-load line displacement curve for one specimen.

It is also convenient to use a compact specimen for such testing, a J approximation which is the same as that used for the bend specimen is employed. Merkle and Corten[5] find, however, there is an effect from the axial forces present in a compact tension specimen and have proposed a plasticity correction for this effect.

$$J = \frac{\eta_r A + \eta_c (P_c \Delta_c - A)}{bB} \tag{6}$$

where P_c is the critical load, Δ_c is the critical displacement, and η_r and η_c are plasticity energy coefficients. With such plastic corrections included in the evaluation, its use is not restricted to deeply notched specimens.

<u>Detection of Stable Crack Growth</u>

Detection of the initiation of stable crack growth during the test has been shown to be a critical component in experimentally determining J_{IC}. Although various methods have been tried, none has proven foolproof, other than a visual examination.

The attainment of maximum load in the test would normally have been an obvious and convenient choice of crack growth criterion. This is indeed the best choice when the specimen behaves in a linear elastic fashion. For the material in this study, linear elastic conditions are only approached well below room temperature. Only then can maximum load be chosen as the point for initiation of stable crack growth.

Veerman and Muller[6] studied the apparent rotation point, the "hinge point" of movement in a bend type specimen, during fracture toughness testing. As long as the crack has not started to propagate, the hinge point of movement will not shift. Geometric considerations provide that the output produced by clip gages at the specimen surface and at the load line should remain in proportion until crack initiation commences. Plotting one gage versus the other will produce first a small linear portion up to general yielding, and a second linear segment up until ductile tearing, locating Δ_c. Although twin gages were utilized in the present study, no reliable results were drawn from their use.

The compliance of fracture toughness specimens is a function of their crack length, therefore compliance is another possible measure of this sensitivity and thus crack length. Theoretical predictions of compliance as a function of crack length have been made by Gross, et al.[7] If a specimen is unloaded periodically at less than 10% of its calculated limit load, and unloading compliance is measured, a marked change during the test would bracket the location of the initiation of ductile tearing. The expression used is

$$\Delta a = \frac{b \, \Delta C}{2 \, C_{ave.}}$$

where Δa is the change in crack length, ΔC is the change in compliance, and $C_{ave.}$ is the average compliance of that specimen prior to crack growth. Tests using this method have thus far been found difficult.

Direct Examination of Crack Growth

Begley and Landes[8] have suggested that direct observation of crack extension be used to determine the measurement point for J_{IC}. J should be calculated for each of a series of specimens using Equation 4 and then plotted versus Δa. Begley and Landes propose that this curve will always take a specific form. A stretch zone will occur prior to ductile tearing. This zone permits a slight apparent change in Δa but no actual material separation. The profile of this stretch zone is shown in Figure 2. Specimens that are only loaded into the domain where stretch zone occurs are expected to fall on the line:

$$J = \partial \sigma_f \, \Delta a \qquad (8)$$

where $\sigma_f = (\sigma_y + \sigma_{UTS})/2$. The deviation from this line is due to stable crack growth. The intersection of the linear and non-linear segments of the J versus Δa curve represents the initiation of stable crack growth, and that point where we calculate J_{IC}. Prudent loading of specimens can produce a value that falls very close to the intersection. In each case, a visual examination of the fractured specimen surface will reinforce that the stretch zone has or has not occurred. Figure 3 shows a sample J versus Δa curve.

TEST PROGRAM AND MATERIALS

The material characterization undertaken compared two strength levels of a particular heavy section steel. Past studies by Gillespie[1] covered fracture toughness characterization of A508 forgings. The present study examines the rolled plate with similar steel chemistry. Therefore, comparisons can be made between the materials in the present study and that in the past study.

It was originally intended that a heat of steel with chemistry filling the specifications of A533B plate might be delivered for testing at two different heat-treated strength levels. One strength level, Class 1, is the lower strength level condition presently acceptable for pressure vessel use from the toughness point of view. Class 2 material reaches a higher strength level but is still expected to show good toughness.

When the program was initiated, only a single heat of A533 Grade B material was on hand, and only at the Class 2 strength level. It was undertaken to retemper a portion of this material to reduce it to Class 1 strength levels. After various attempts it unfortunately was found to be impossible. Therefore a second heat of steel was eventually obtained much later, at both Class 1 and Class 2 strength levels. All tests on Class 2 plate came from the first heat and all Class 1 tests came from the second.

Lukens Steel provided both heats of material tested in this study. Plate sections arrived in 203 mm (8 inch) thick sections, each 609 mm (2 feet) square.

The heat treat schedule used by Lukens is as follows:

harden: 899°C (1650°F ± 25°F)

held for 1 hour per each inch of thickness, then water quenched.

temper: 671°C (1240°F) Class 1

649°C (1200°F) Class 2

held for 1 hour per inch of thickness.

Chemical analysis of each heat and information provided by Lukens Steel are provided in Table I.

TESTING PROCEDURES AND RESULTS

Metallographic Examination

This examination, like all other tests, was performed on material sectioned from the quarter thickness of the plate. Besides providing general information on the microstructure, this metallography verified that the steel had the microstructure normally expected in heavy plate sections. It was also necessary to establish close similarity between the two heats being tested.

Small cubes of plate material were mounted in bakelite, with the particular polished surface oriented in the L-S direction. This corresponds to the same plane of fracture planned for the notched specimens. Mounts were rough belt ground to a flat surface in preparation for hand grinding. The cylindrical mounts were chamfered at the edges to protect polishing laps from sharp edges. Wet grinding was then carried out with 240, 320, 400, and 600 grit silicon carbide papers. Further polishing was done on wheels with 1μ alumina, Linde A, and finally Linde B aluminas. Having removed all scratches from the specimen surface, the specimen was cleaned with soap and water, dried in methanol and etched. Alternate etching, light polishing, and re-etching removed the disturbed metal from the surface. The etching technique used was the total emersion of the polished surface into the etchant. First 4% picral was used and then 2% nital. Photomicrographs were taken on the Zeiss Axiomat Metallograph on black and white polaroid PN 55 film. A533 Grade B Class 1 and Class 2 materials are shown in Figure 4 at 500X.

Tensile Testing

Fracture toughness characterization requires data on the yield and tensile strengths of the test material at various temperatures as parameters. Therefore, tensile properties were surveyed over the range of temperatures of interest, $-129^{\circ}C$ to $100^{\circ}C$ ($-200^{\circ}F$ to $212^{\circ}F$), as required by ASTM E8 and A270. Standard 6.35 mm (.250 inch) diameter buttonhead specimens were machined from the quarter thickness of the plate. Tensile specimens were taken with the plate rolling direction, and with all the gage lengths taken several inches away from any burned plate edge. Tests were performed on the Instron tensile machine with a 44.4 KN (10,000 pound) load cell. Crosshead speed was 5 mm/min (.2 inches/min.). Low temperatures were achieved by holding the tensile specimen in a bath of 2-methylbutane plus liquid nitrogen, kept at -129°C (-200°F) or a bath of methanol plus liquid nitrogen kept at -46°C (-50°F). Room temperature tensiles were run as well as tests in a small electric resistance furnace kept at 100°C (212°F). Temperatures were controlled within 3°C (5°F).

For each specimen, ultimate tensile strength, yield strength, percent elongation, and percent reduction in area were determined. Results of these tests are tabulated in Table II and are plotted as a function of temperature in Figure 5.

Charpy V-Notch Impact Testing

Impact tests were run on both Class 1 and Class 2 material. Quarter thickness cuts were taken and machined into standard size Charpy blanks as per ASTM Specifications A 370 and E 23. A certified calibrated 325 J (240 ft-lb) Satec model ST-1 testing machine was used. Data taken from each test included energy absorbed, percent fibrous fracture, and lateral expansion. Figures 6 through 8 contain Class 1 results. Figures 9 through 11 contain Class 2 results. The transition curves drawn through the data points are computed least square sigmoidal curves as calculated by a computer program on file at Lehigh University. A data summary is given in Table III.

Drop Weight Specimens

Procedures designated by ASTM E 208-69 were followed in determining the nil-ductility transition temperatures, with P-3 size specimens chosen. Results of these tests are presented in Table IV.

FRACTURE TOUGHNESS TESTING

Specimen Preparation

Quarter thickness material was once again chosen in preparing fracture toughness specimens. In accordance with ASTM E 399, 38 mm (1.5 inch) compact tension specimens were machined in the L-T orientation, so that the final fracture plane would occur with the rolling direction.

Some refinements in specimen detail were initiated with the present study. Previous programs encountered problems with uniformity in specimen knife edges. A new configuration allows for precision grinding of the specimen in producing both sets of knife edges required for twin gage analysis. Figure 12 illustrates the specimen detail.

A necessity in performing a fracture toughness test is a sharp crack tip for fracture initiation. All specimens tested were precracked on an Amsler Vibrophore fatigue testing machine in accordance with load ranges listed in ASTM E 399. Final stage stress intensities were of course kept below those maximum levels permitted.

Test Procedure

Tests were performed on a 533 KN (120,000 lb.) Baldwin Universal testing machine. Load versus load line displacement was recorded on a Hewlett-Packard X-Y recorder. In several cases, the same data was punched onto computer tape by an analog-to-digital recorder. Load was monitored by a cell consisting of strain gages mounted on the column of the Baldwin testing machine. Load line displacement and face displacement were measured with cantilever beam clip gages. When temperature measurements were needed, during heating or cooling, they were charted on a Sargent recorder using a copper-constantan thermocouple.

Low temperature tests were run by enclosing the grips, specimen, and gages in a specially designed and insulated chamber, through which liquid nitrogen was pumped. The thermocouple was placed in a hole inside the specimen to measure the cooling of the specimen. Temperatures were achieved by increasing, restricting, and finally stopping the flow of liquid nitrogen. Tests run at $100^{o}C$ ($212^{o}F$) were conducted by enclosing the specimen and grips within a portable electric furnace with a circulating fan. Test temperatures were well controlled to within $3^{o}C$ ($5^{o}F$) for all tests. Each specimen was held at temperature for 15 minutes after the test temperature had been reached.

Previous programs studied the feasibility of the various J-integral determination techniques. The method adopted in the present study was the best possible with our existing equipment. A total of 20 compact tension specimens were to be tested for each particular steel. Five were run at each of four temperatures to cover the full range of material use. Each of the five specimens produced a single data point for the J versus Δa curve. A particular specimen was mounted in the machine grips and brought to the test temperature. Loading the specimen at a constant rate, the specimen was loaded to a pre-determined load level. With all the gages and recorders still operating, the specimen was unloaded. Each test provided a curve containing load versus load line deflection data on both an X-Y recorder and computer tape. All this information provided a measure of unloading compliance, maximum load, and maximum load line deflection for that particular test and thus a particular J-value. For tests to be carried out to further loading, several unloading compliance measurements were taken before final unloading. These longer tests were run by loading up to maximum load, after which ductile tearing resulted. After prescribed loading and unloading was completed, specimens were heat tinted by placing them in a 427°C (800°F) furnace for 1½ hours. This served to blacken that portion of the fatigue crack plus crack extension that was present up until loading was concluded. After heat tinting, specimens were cooled to liquid nitrogen temperatures and broken open totally using the Baldwin test machine once again.

Data Analysis

Data reduction took two avenues. In those cases where data had been punched onto computer tape, special procedures were used to repunch data onto cards, then convert digital data cards to calibrated load and load line displacement values also on data cards.

After sorting, the entire test could be reconstructed as a series of data points, each one second apart. Loading or unloading portions of the data cards were selectively used for appropriate calculations.

As mentioned, detection of the critical location where crack propagation first started is the important item in J-integral analysis. Direct visual examination of the fracture surface of each specimen revealed any possible crack extension as a darkened area created by the heat tinting. Under a microscope with a calibrated eyepiece, the crack extension could be traversed and thus measured. Various locations across the samples were measured in search of a spot where the greatest amount of extension occurred. In those cases where no true extension occurred, the stretch zone itself could be measured by the microscope technique. In both cases the Tukon microhardness tester provided the calibrated microscope and table needed for crack measurement. Low temperature tests proved most difficult when any crack extension was measured due to the minuteness of the stretch zone.

The specimen having been laid open, it was then easy to measure the actual specimen dimensions, thus getting the most precise average measure of a, the total crack length. Recall that for each specimen, where configurations vary slightly, a different set of plastic correction factors are chosen for each C/a ratio.

Whether the computer output data was used or the analysis was made directly from the load-load line plot, the values needed were maximum load reached, total displacement of the specimen at the load line, and plastic energy consumed, A, measured as the area under the load displacement plot. All of these values, as used in Equation (6), were employed to calculate J values for each loading condition. With a range of specimens, each one giving its own J value, all that remained was to reduce the available data to one critical value, J_{IC}. For tests at room temperature and at $100^{o}C$ ($212^{o}F$) sufficient plasticity allowed for measurable stretch zone and crack propagation. For these cases, J_{IC} was defined as that J value corresponding to the intersection of the two sloped sections of the J versus Δa curve. Figures 13 through 16 contain such curves for Class 1 and Class 2 materials. Below room temperature, tests showed little or no crack extension prior to fracture, therefore the critical spot where crack propagation is predicted to have started was at maximum load. No J versus Δa curve could be constructed. The results of these tests are presented in Tables IV and V. J_{IC} values are converted to equivalent K_J values according to Equation (3). As intended, with J_{IC} determined over a range of temperatures, the K_{IR} curve, normalized to nil ductility temperature can be drawn.[9] Class 1 and Class 2 curves are compared in Figures 17 and 18.

DISCUSSION AND CONCLUSIONS

The two heats which were used in these experiments had very similar chemistries, although not identical. Even with the standardized treatments that Lukens Steel uses with its plate products, variations in mechanical behavior are found across the chemical range specified for A533 Grade B plate. For example, Class 2 plate from heat D3010 exhibited a higher yield strength and a lower tensile strength than Class 2 material from heat B9670-1. As Figure 5 shows, Class 2 material is a generally higher strength level than Class 1.

Both heats (Classes) tested exhibited the same NDT temperature, -23°C (-10°F), but different Charpy impact transition temperatures. Up until now, Class 1 material has been chosen as an acceptably tough material. However, the present study shows that the Class 2 material tested exhibited better Charpy impact results than Class 1 material. Class 2 exhibited a shelf energy of 195 joules (145 ft-lb) with Class 1 only resulting in 170 joules (125 ft-lb). Class 2 material also showed a significantly lower transition temperature.

Fracture toughness calculations carried out using Equations 5 and 6 yielded different results. Therefore the results reported in all tables and figures are results of Equation 6, relying on plastic correction factors. In all cases, values were higher for Equation 6.

The investigation had no success with the twin gage calculations. No outstanding blips occurred on any of the chart recordings that could be correlated with any known Δ critical. Unloading compliance failed also, probably due to shifts in the seating of the clip gages and noise in chart recorder amplifiers.

Great success has been found with visual examination of fracture surfaces in conjunction with heat tinting. For the two higher temperatures tested, stretch zones could be more easily detected. Below room temperature, lack of stretch zones or appreciable crack growth precluded J versus Δa curves. Maximum load used as a crack growth criteria was the closest approximation. Unfortunately, on high temperatures, only one J_{IC} value and thus one K_J value was calculated. At the lower temperatures, each test provided a J_{IC} value and finally a better statistical average K_J.

As predicted by the superior Charpy impact results of the Class 2 material, the fracture toughness results showed Class 2 material to be superior. At every temperature tested, Class 2 registered better toughness. Both materials showed toughness values that increased with temperature up until room temperature where values leveled off to 232 MPa$\sqrt{m}$ (211 Ksi$\sqrt{in}$) for Class 1 and 240 MPa$\sqrt{m}$ (224 KSI$\sqrt{in}$) for Class 2. For the three lower temperatures listed, all toughness values remained above the normalized K_{IR} curve. Therefore at 100°C, (212°F) both materials fail the K_{IR} criterion. In view of the acceptable fracture toughness at low temperatures and remembering that Class 2 material was as good as Class 1 material even at 100°C, Class 2 plate is just as good a candidate for pressure service as Class 1.

TABLE I

Composition and Mechanical Properties of A533 Grade B

Data Supplied by Lukens Steel Company

Composition (%)

Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al
B9670	.24	1.35	.007	.008	.23	.66	.14	.59	.15	.035
D3010	.20	1.32	.014	.005	.24	.67	.15	.56	.17	.040

Tensile Properties (¼T)

Heat and Class	Yield Strength (Ksi)	Tensile Strength (Ksi)	Elong. (%)	Red. Area (%)
B9670-1 Class 2	78.0	106.0	24	69.0
D3010-2B Class 1	70.4	93.5	24	70.5
D3010-2C Class 2	80.5	101.5	23	70.4

70°F Impact Properties (¼T longitudinal)

Heat and Class	Energy (ft-lb)	Expansion (Mils)	Appearance (% Shear)
B9670-1 Class 2	143-143-141	97-96-93	90
D3010-2B Class 1	118-118-116	81-84-83	90
D3010-2C Class 2	110-110-108	81-78-83	80

TABLE II

TENSILE PROPERTIES OF TEST MATERIALS

A533 Grade B Class 1 (D3010)

Specimen No.	Temperature ^{o}C	(^{o}F)	Yield Strength MPa	(Ksi)	Tensile Strength MPa	(Ksi)	% Elong. %	% Red. of Area, %
2	100	(212)	431	(62.5)	574	(83.2)	26	70
3	100	(212)	436	(63.3)	576	(83.5)	28	73
	average		434	(62.9)	575	(83.4)	27	72
4	21	(70)	451	(65.4)	601	(87.2)	27	73
5	21	(70)	450	(65.2)	597	(86.6)	26	69
	average		451	(65.3)	599	(86.9)	27	71
6	-46	(-50)	487	(70.7)	656	(95.1)	26	71
9	-46	(-50)	499	(72.3)	665	(96.5)	24	70
	average		493	(71.5)	661	(95.8)	25	71
7	-129	(-200)	648	(94.0)	779	(113.0)	30	68
8	-129	(-200)	645	(93.6)	780	(113.1)	29	65
	average		647	(93.8)	780	(113.1)	30	67

TABLE II - TENSILE PROPERTIES OF TEST MATERIALS (continued)

A533 Grade B Class 2 (B9670)

Specimen No.	Temperature °C (°F)	Yield Strength MPa	Yield Strength (Ksi)	Tensile Strength MPa	Tensile Strength (Ksi)	% Elong. %	% Red. of Area, %
7	-129 (-200)	690	(100.)	853	(124.)	14	65
8	" "	733	(106.)	858	(125.)	33	63
9	" "	647	(93.9)	822	(119.)	*	64
	average	690	(100.)	844	(123.)	24	64
5	-46 (-50)	551	(79.9)	747	(108.)	25	70
6	" "	558	(80.9)	749	(109.)	25	68
	average	555	(80.4)	748	(109.)	25	69
3	21 (70)	511	(74.2)	684	(99.3)	27	71
4	" "	520	(75.5)	685	(99.4)	25	70
	average	516	(74.9)	685	(99.4)	26	71
1	100 (212)	496	(72.1)	653	(94.7)	28	64
2	" "	483	(70.1)	633	(91.9)	16	71
	average	490	(71.1)	643	(93.3)	22	68

*Failed outside of gage marks.

TABLE III

Impact Properties of the Test Materials

(Charpy Impact Test Results (Tangential)

Steel	Transition Temperature						Shelf Energy	
	20J °C	(15 ft-lb) (°F)	68J °C	(50 ft-lb) (°F)	.875 mm °C	(35 Mil) (°F)	J	(ft-lbs)
A533 Grade B 1	-27	(-17)	12	(54)	-6	(33)	170	(125)
A533 Grade B 2	-99	(-134)	-28	(-14)	-43	(-41)	195	(145)

Drop Weight Test Results (P-3)

Steel	NDTT	
	°C	(°F)
A533 Grade B 1	-23	(-10)
A533 Grade B 2	-23	(-10)

TABLE IV

Fracture Toughness Data for A533 Grade B Class 1

Spec. No.	Temperature °C	(°F)	Failure Mode	Δa mm	(mils)	J KJ/m^2	J ($\frac{in\text{-}lb}{in^2}$)	J_{IC} KJ/m^2	J_{IC} ($\frac{in\text{-}lb}{in^2}$)	K_J MPa$\sqrt{m}$	K_J (Ksi$\sqrt{in}$)
21	21	(70)	1	.9	(35.)	328.5	(1875)				
44	"	"	2	.45	(18.)	253.9	(1448)				
22	"	"	2	.2	(8.)*	216.9	(1238)				
23	"	"	2	.08	(3.)*	118.8	(678)	236.5	(1350)	232	(211)
24	"	"	2	.03	(1.)*	52.0	(297)				
25	"	"	2	.01	(.4)*	23.1	(132)				
11	100	(212)	2	2.0	(79.)	590.7	(3372)				
12	"	"	2	1.3	(51.)	444.6	(2538)				
13	"	"	2	1.0	(39.)	316.0	(1804)	227.7	(1300)	228	(207)
45	"	"	2	.50	(20.)	266.0	(1520)				
14	"	"	2	.2	(8.)*	181.8	(1038)				
15	"	"	2	.07	(3.)*	69.4	(396)				

continued - - -

1. Specimen fracture before or at max. load, little plasticity.
2. Specimen does not fracture or does so only after appreciable crack growth.

* Crack growth within limits of stretch zone, $J = 2\sigma_f \Delta_a$. Not considered true crack growth.

TABLE IV - Fracture Toughness Data for A533 Grade B Class 1 (continued)

Spec. No.	Temperature ^oC	(^oF)	Failure Mode	Δa* mm (mils)	J KJ/m^2	J $(\frac{in\text{-}lb}{in^2})$	J_{IC} KJ/m^2	J_{IC} $(\frac{in\text{-}lb}{in^2})$	K_J $MPa\sqrt{m}$	K_J $(Ksi\sqrt{in})$
32	-46	(-50)	1	0.0	60.4	(345)				
33	"	"	1	0.0	35.4	(202)	42.9	(245)	99	(90)
34	"	"	1	0.0	38.0	(217)				
35	"	"	1	0.0	38.2	(218)				
41	-129	(-200)	1	0.0	8.6	(49)				
42	"	"	1	0.0	14.7	(84)	12.6	(72)	54	(49)
43	"	"	1	0.0	14.7	(84)				

1. Specimen fracture before or at max. load, little plasticity.
2. Specimen does not fracture or does so only after appreciable crack growth.

* Crack growth within limits of stretch zone, $J = 2\sigma_f \Delta_a$. Not considered true crack growth.

TABLE V

Fracture Toughness Data for A533 Grade B Class 2

Spec. No.	Temperature ^oC	(^oF)	Failure Mode	Δ_a mm	(mils)	J KJ/m^2	J $(\frac{in\text{-}lb}{in^2})$	J_{IC} KJ/m^2	J_{IC} $(\frac{in\text{-}lb}{in^2})$	K_J $MPa\sqrt{m}$	K_J $(Ksi\sqrt{in})$
141	-129	(-200)	1	0.0		22.	(124)				
142	"	"	1	0.0		26.	(149)				
143	"	"	1	0.0		46.	(261)	28	(159)	79.6	(72.4)
144	"	"	1	0.0		18.	(103)				
131	-46	(-50)	1	0.10	(4.0)*	205.	(1172)				
132	"	"	2	0.05	(2.0)*	162.	(927)				
133	"	"	1	0.0		53.	(302)	124	(706)	168	(153)
134	"	"	2	0.0		88.	(501)				
135	"	"	1	0.025	(1.0)*	110.	(630)				

continued - - - -

1. Specimen fracture before or at max. load, little plasticity.

2. Specimen does not fracture or does so only after appreciable crack growth.

* Crack growth within limits of stretch zone, $J = 2\sigma_f \Delta_a$. Not considered true crack growth.

TABLE V - Fracture Toughness Data for A533 Grade B Class 2(continued)

Spec. No.	Temperature ^oC	(^oF)	Failure Mode	Δ_a mm	(mils)	J KJ/m^2	($\frac{in\text{-}lb}{in^2}$)	J_{IC} KJ/m^2	($\frac{in\text{-}lb}{in^2}$)	K_J $MPa\sqrt{m}$	($Ksi\sqrt{in}$)
121	21	(70)	2	0.0		25.7	(147)				
122	"	"	2	0.062	(2.44)*	98.9	(565)				
123	"	"	2	0.145	(5.71)*	147.	(839)	249	(1420)	240	(218)
124	"	"	2	0.185	(7.28)	256.	(1460)				
125	"	"	2	0.611	(24.1)	399.	(2280)				
126	"	"	2	0.460	(18.1)	327.	(1860)				
111	100	(212)	2	0.235	(9.30)	259.	(1480)				
112	"	"	2	0.782	(30.8)	399.	(2280)				
113	"	"	2	0.161	(6.34)*	147.	(837)	266	(1520)	246	(224)
114	"	"	2	0.046	(1.81)*	47.7	(272)				
115	"	"	2	0.414	(16.3)	327.	(1868)				

1. Specimen fracture before or at max. load, little plasticity.
2. Specimen does not fracture or does so only after appreciable crack growth.

* Crack growth within limits of stretch zone, $J = 2\sigma_f \Delta_a$. Not considered true crack growth.

Development of J vs Δ Curves

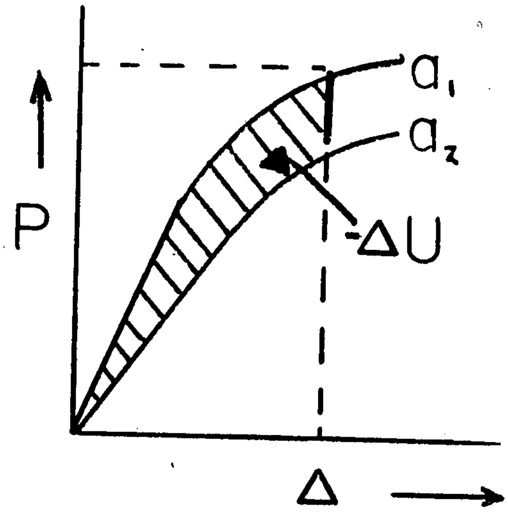


Fig. 1a

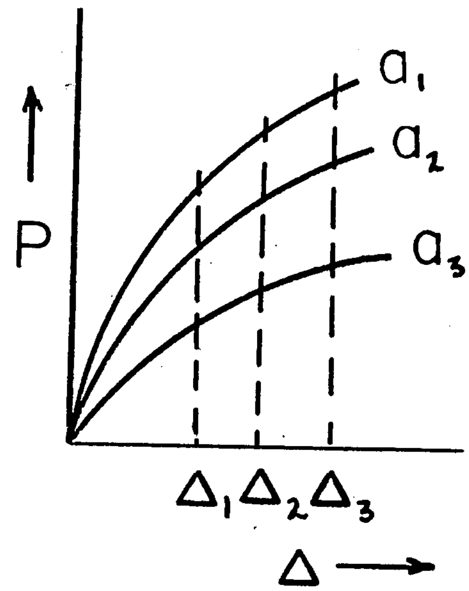


Fig. 1b

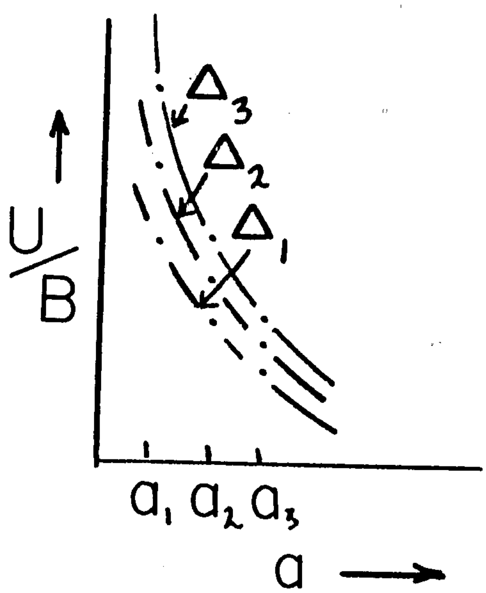


Fig. 1c

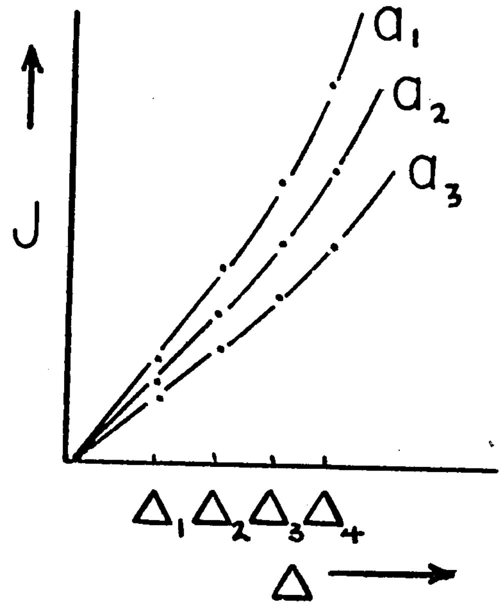


Fig. 1d

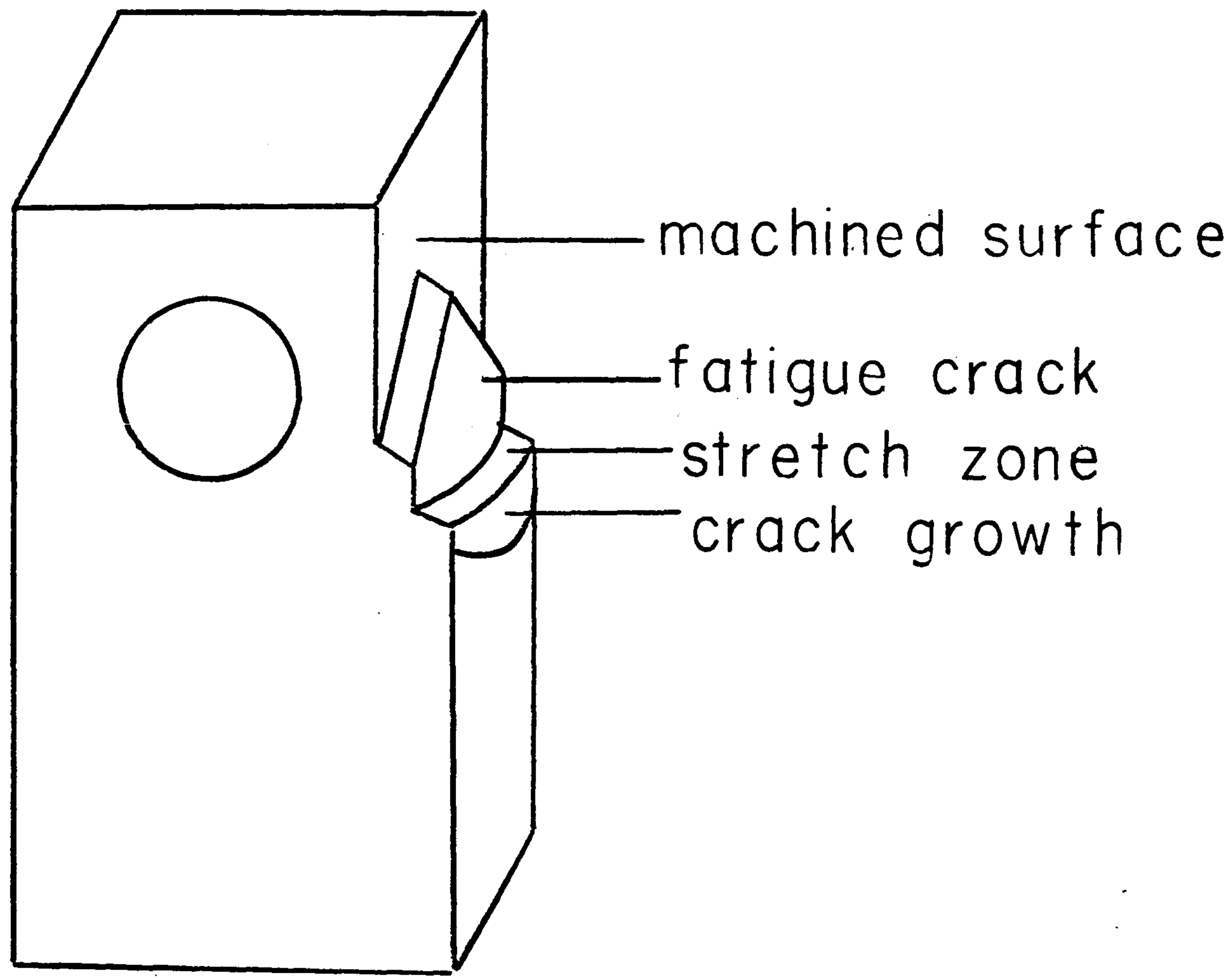


Fig. 2 Profile of Compact Tension Specimen

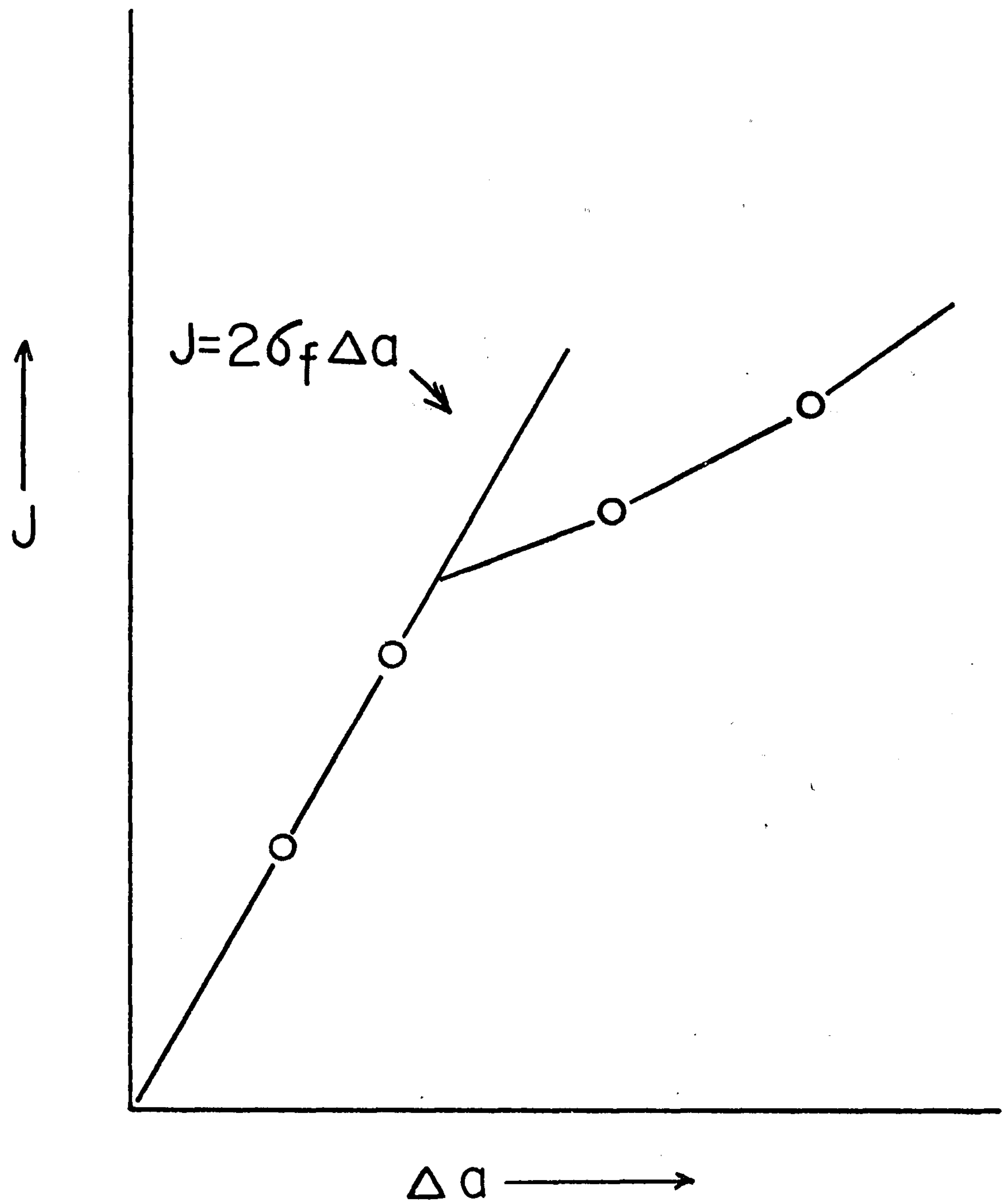
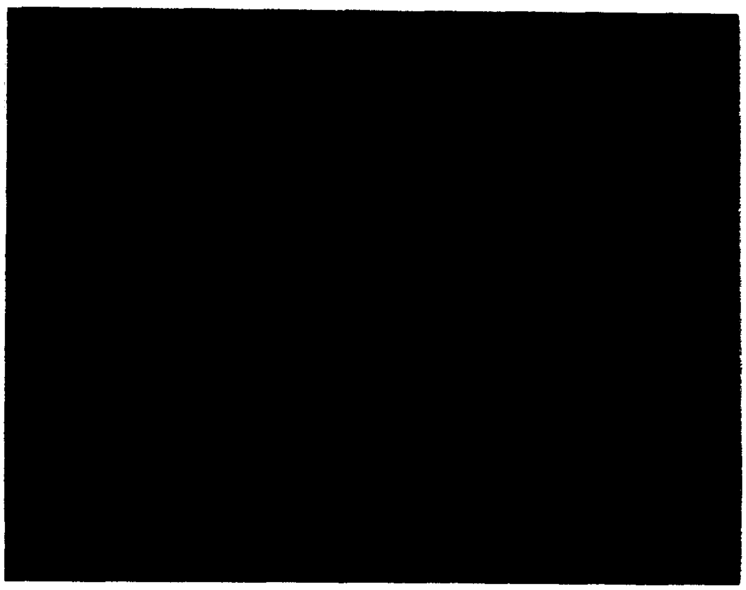


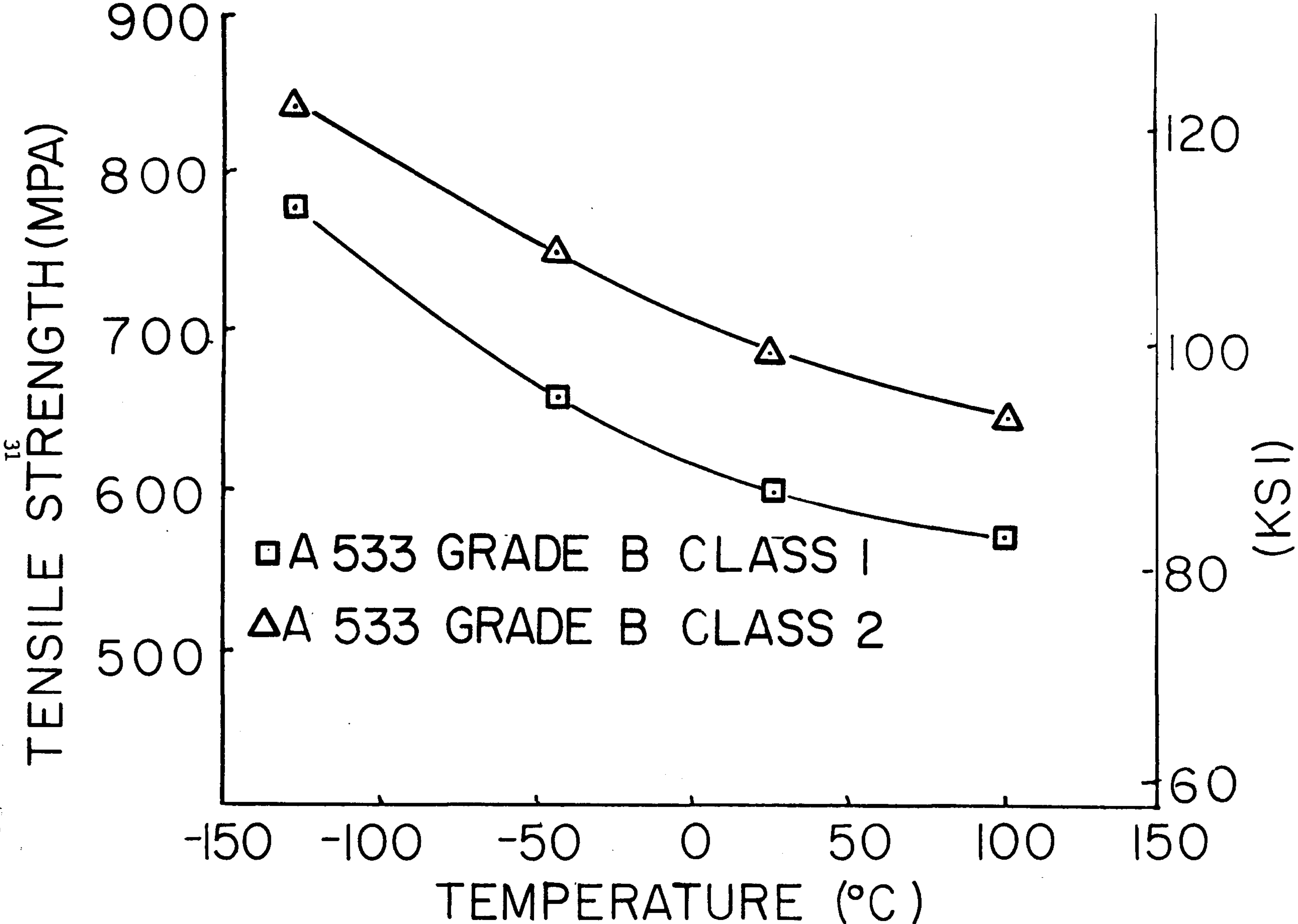
FIGURE 3 J VERSUS Δa CURVE

A. Carbide Structure of A533 Grade B Class 1 (4% picral 2% nital) 500X.



B. Carbide Structure of A533 Grade B Class 2 (4% picral 2% nital) 500X.

Figure 4 Photomicrographs of A533 Grade B Plate Materials



900
800
700
600
500
TENSILE STRENGTH (MPA)
120
100
80
60
(KSI)
-150
-100
-50
0
50
100
150
TEMPERATURE (°C)
□ A 533 GRADE B CLASS 1
Δ A 533 GRADE B CLASS 2

FIG. 5a

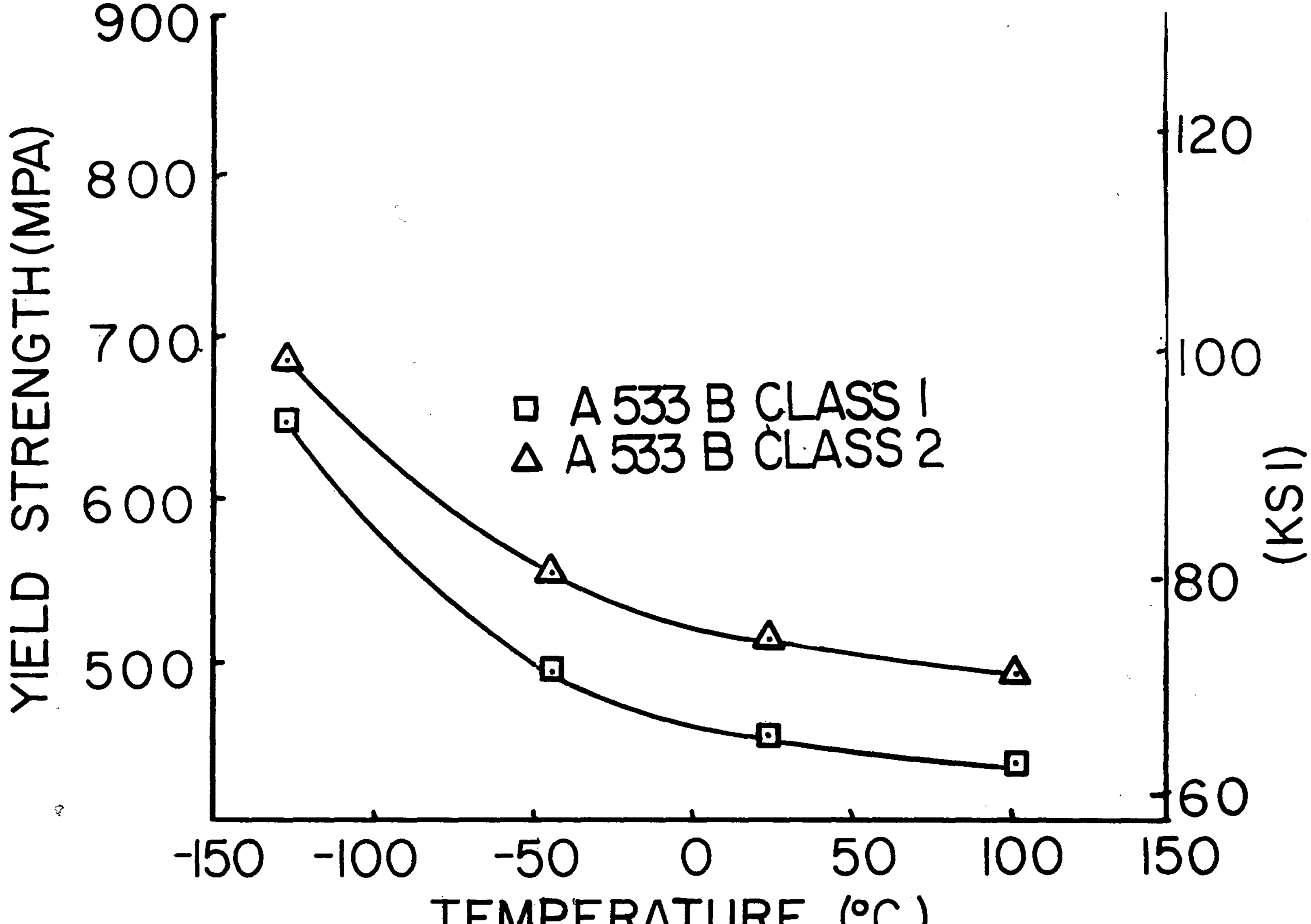

YIELD STRENGTH (MPA)
900
800
700
600
500
(KSI)
120
100
80
60
A 533 B CLASS 1
A 533 B CLASS 2
-150
-100
-50
0
50
100
150
TEMPERATURE (°C)

FIG. 5 b

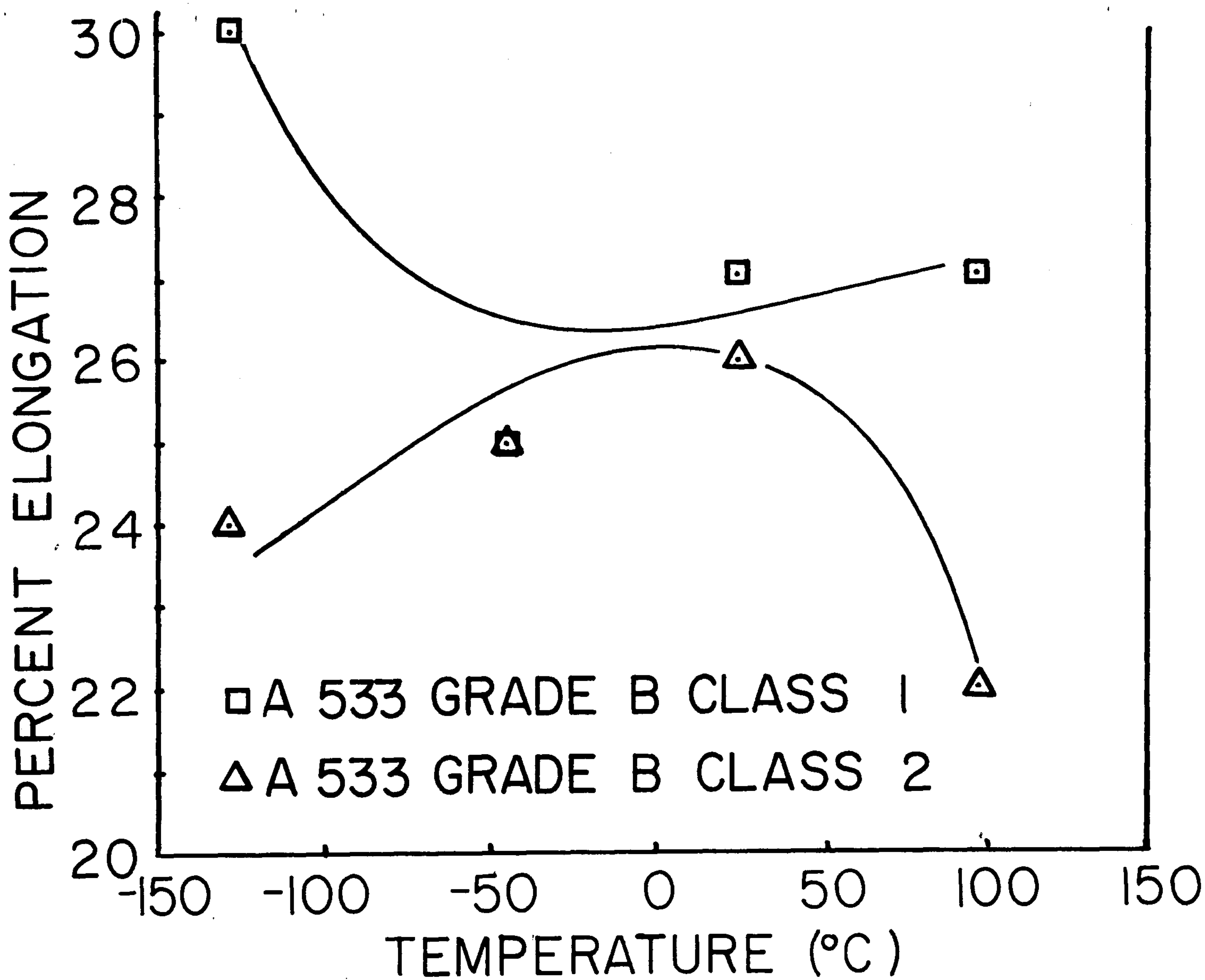

30
28
26
24
22
20
PERCENT ELONGATION
-150
-100
-50
0
50
100
150
TEMPERATURE (°C)
□ A 533 GRADE B CLASS 1
△ A 533 GRADE B CLASS 2

FIG. 5c

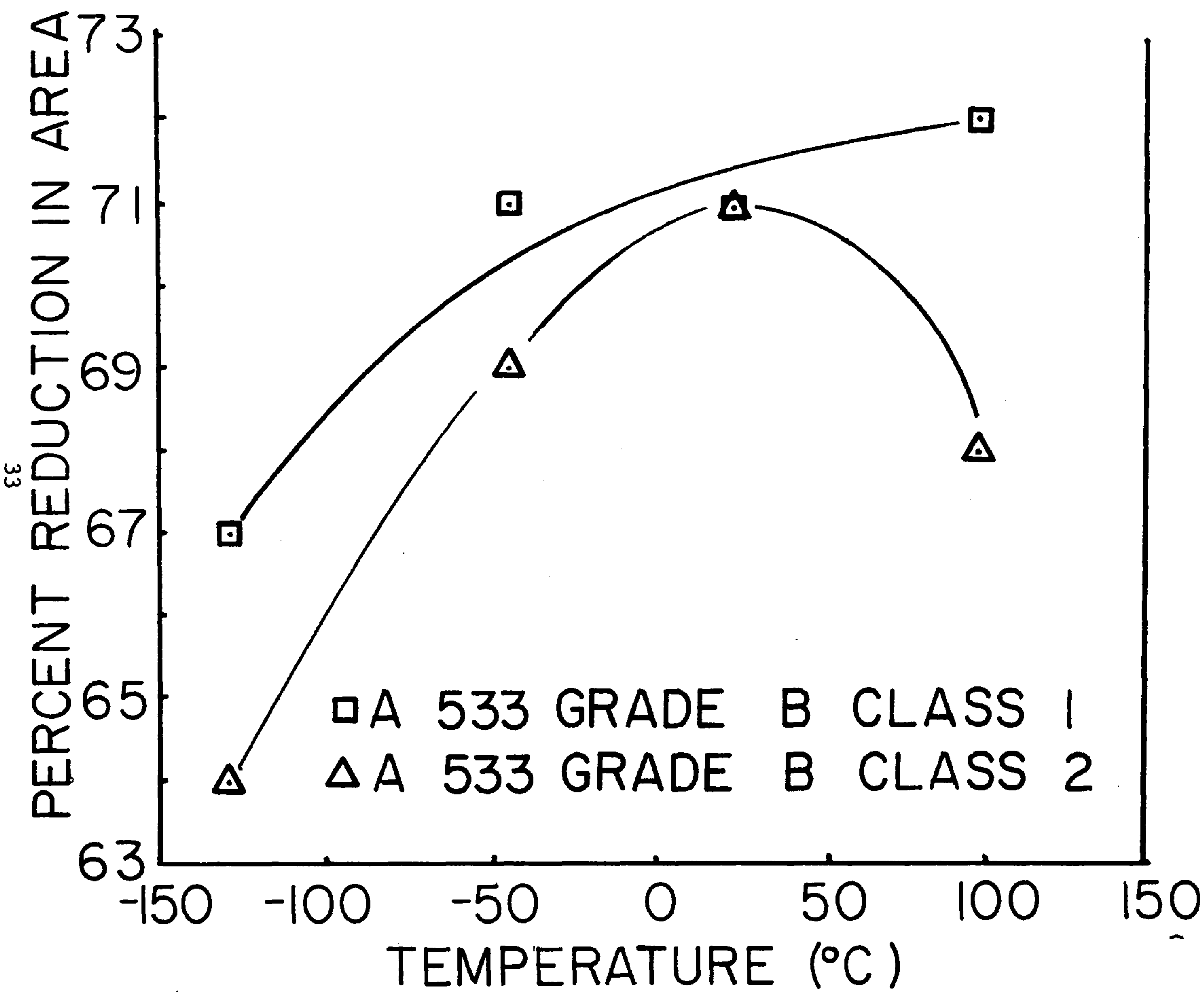

PERCENT REDUCTION IN AREA
73
71
69
67
65
63
-150
-100
-50
0
50
100
150
TEMPERATURE (°C)
A 533 GRADE B CLASS 1
A 533 GRADE B CLASS 2

FIG. 5d

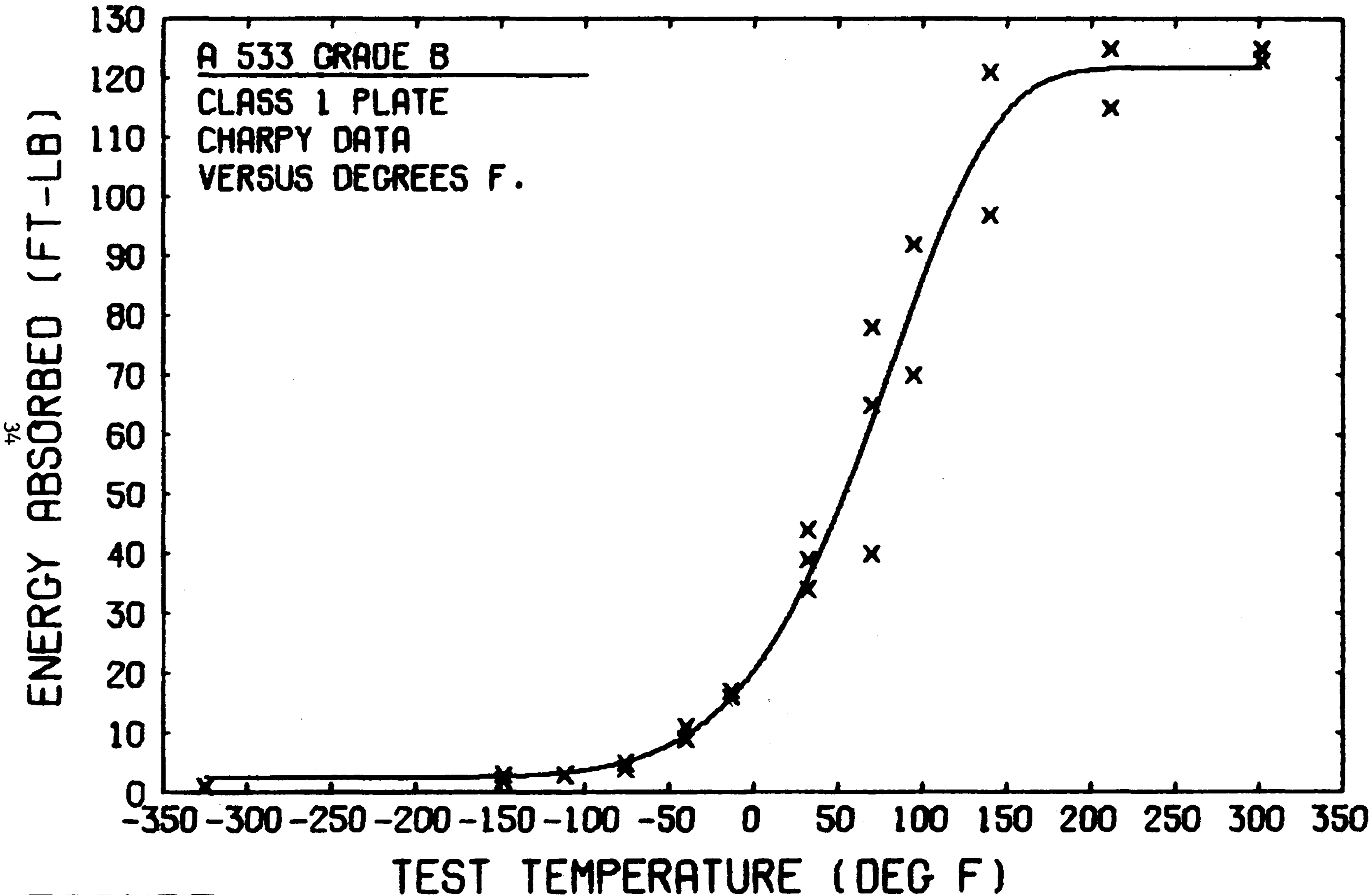

A 533 GRADE B
CLASS 1 PLATE
CHARPY DATA
VERSUS DEGREES F.
ENERGY ABSORBED (FT-LB)
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-350 -300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350
TEST TEMPERATURE (DEG F)

FIGURE 6a

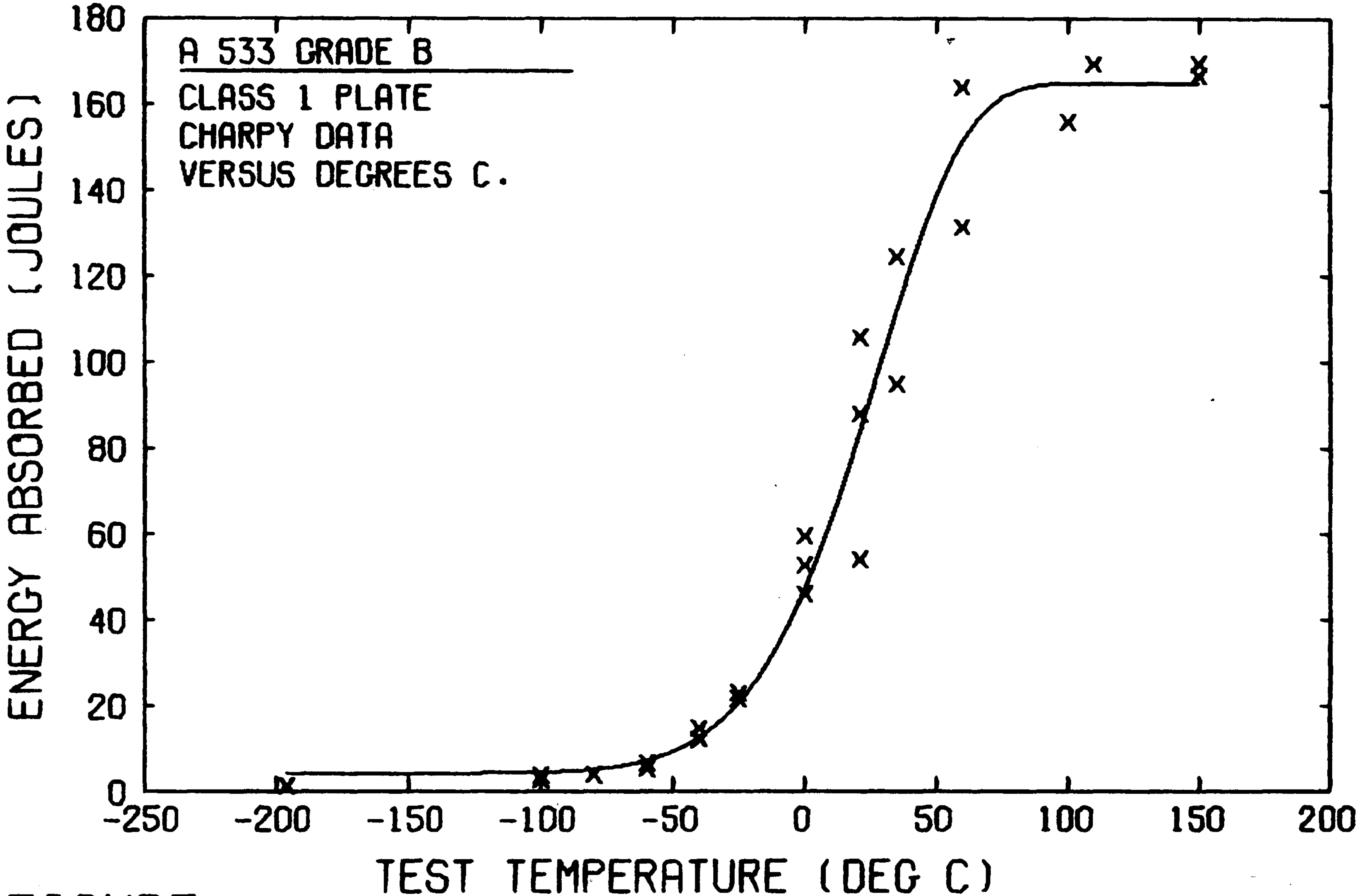

A 533 GRADE B
CLASS 1 PLATE
CHARPY DATA
VERSUS DEGREES C.
ENERGY ABSORBED (JOULES)
0
20
40
60
80
100
120
140
160
180
-250
-200
-150
-100
-50
0
50
100
150
200
TEST TEMPERATURE (DEG C)

FIGURE 6b

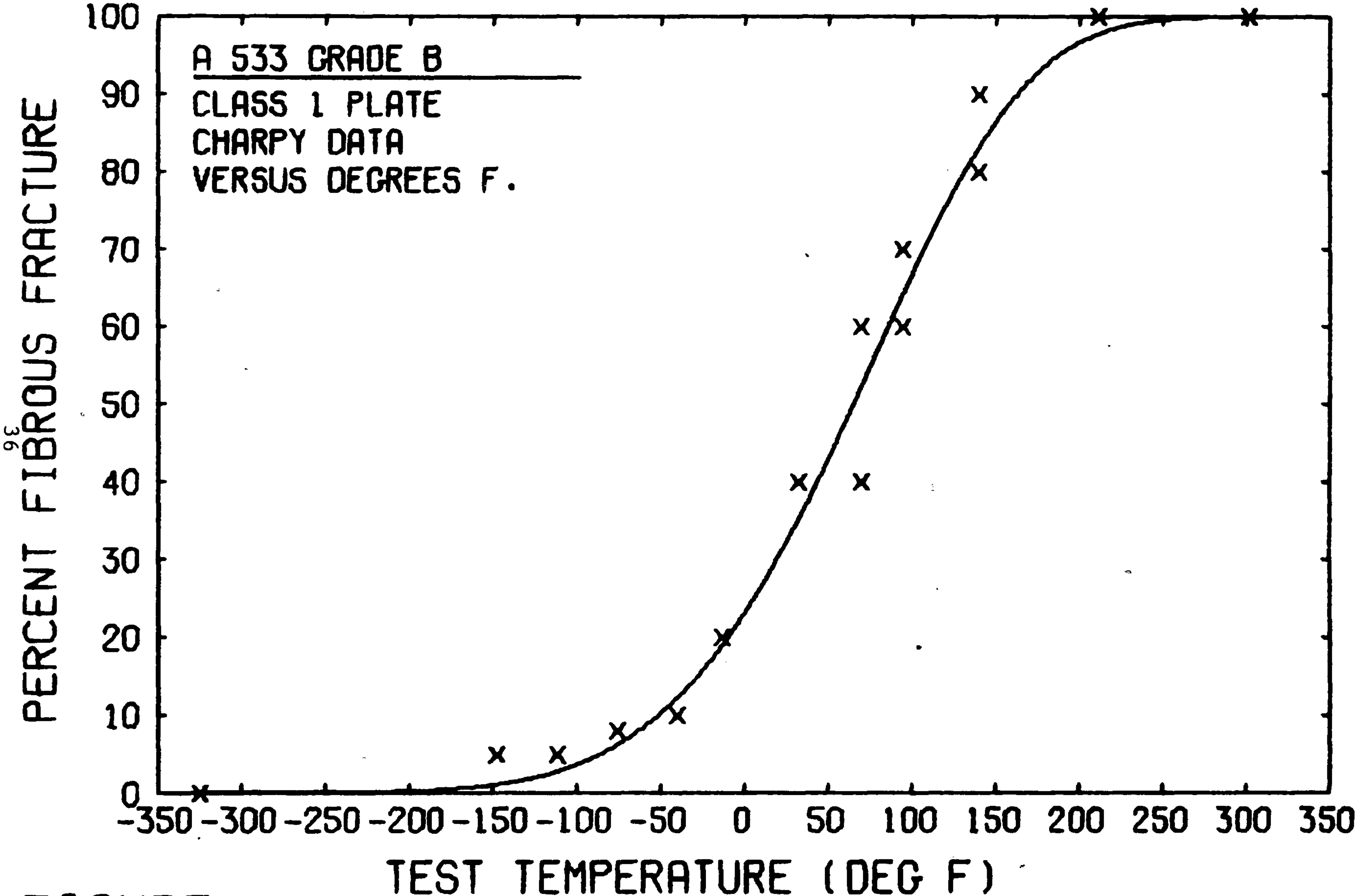
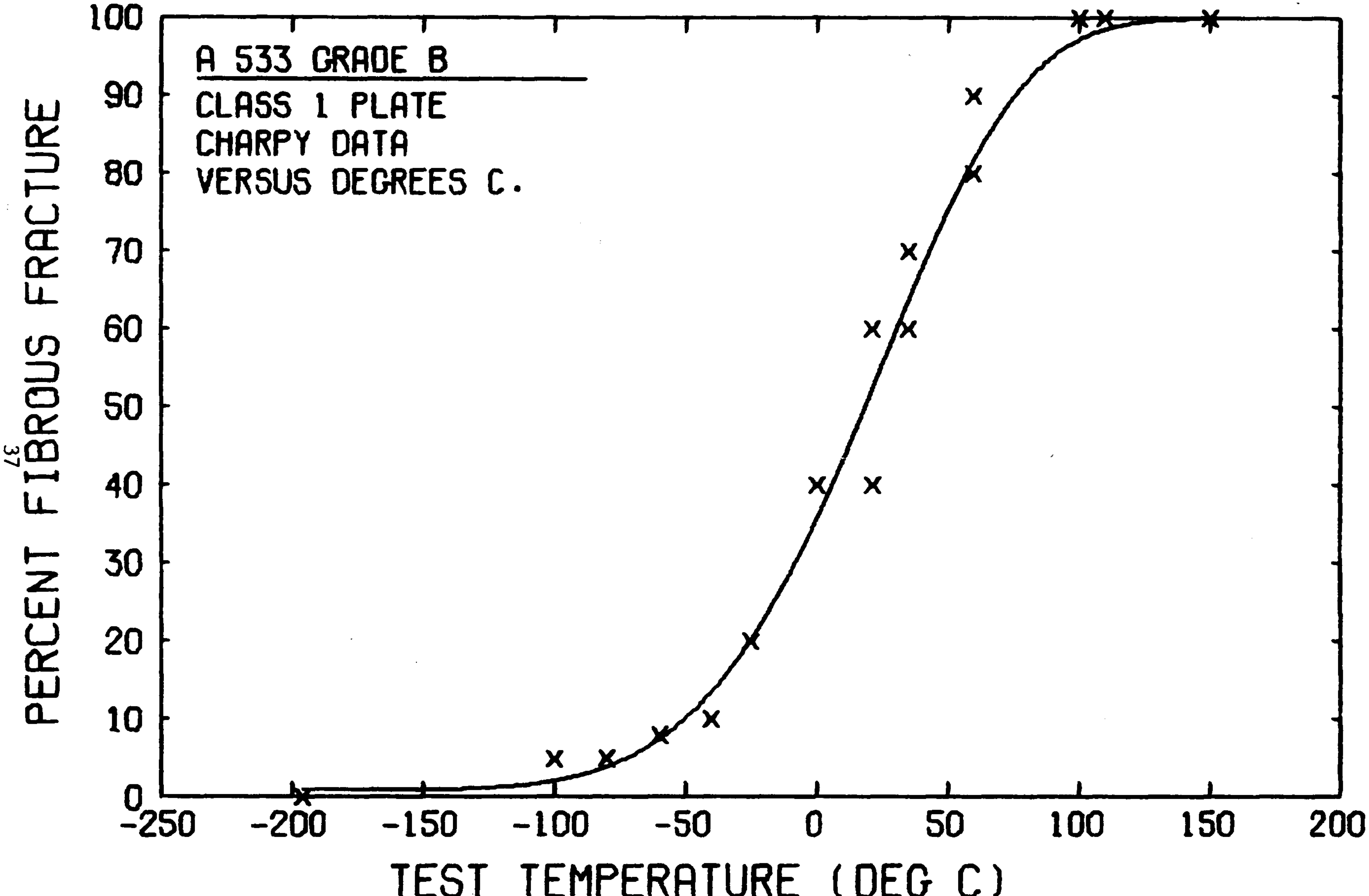

A 533 GRADE B
CLASS 1 PLATE
CHARPY DATA
VERSUS DEGREES F.
PERCENT FIBROUS FRACTURE
100
90
80
70
60
50
40
30
20
10
0
-350 -300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350
TEST TEMPERATURE (DEG F)

FIGURE 7a



A 533 GRADE B
CLASS 1 PLATE
CHARPY DATA
VERSUS DEGREES C.
PERCENT FIBROUS FRACTURE
0
10
20
30
40
50
60
70
80
90
100
-250
-200
-150
-100
-50
0
50
100
150
200
TEST TEMPERATURE (DEG C)

FIGURE 7b

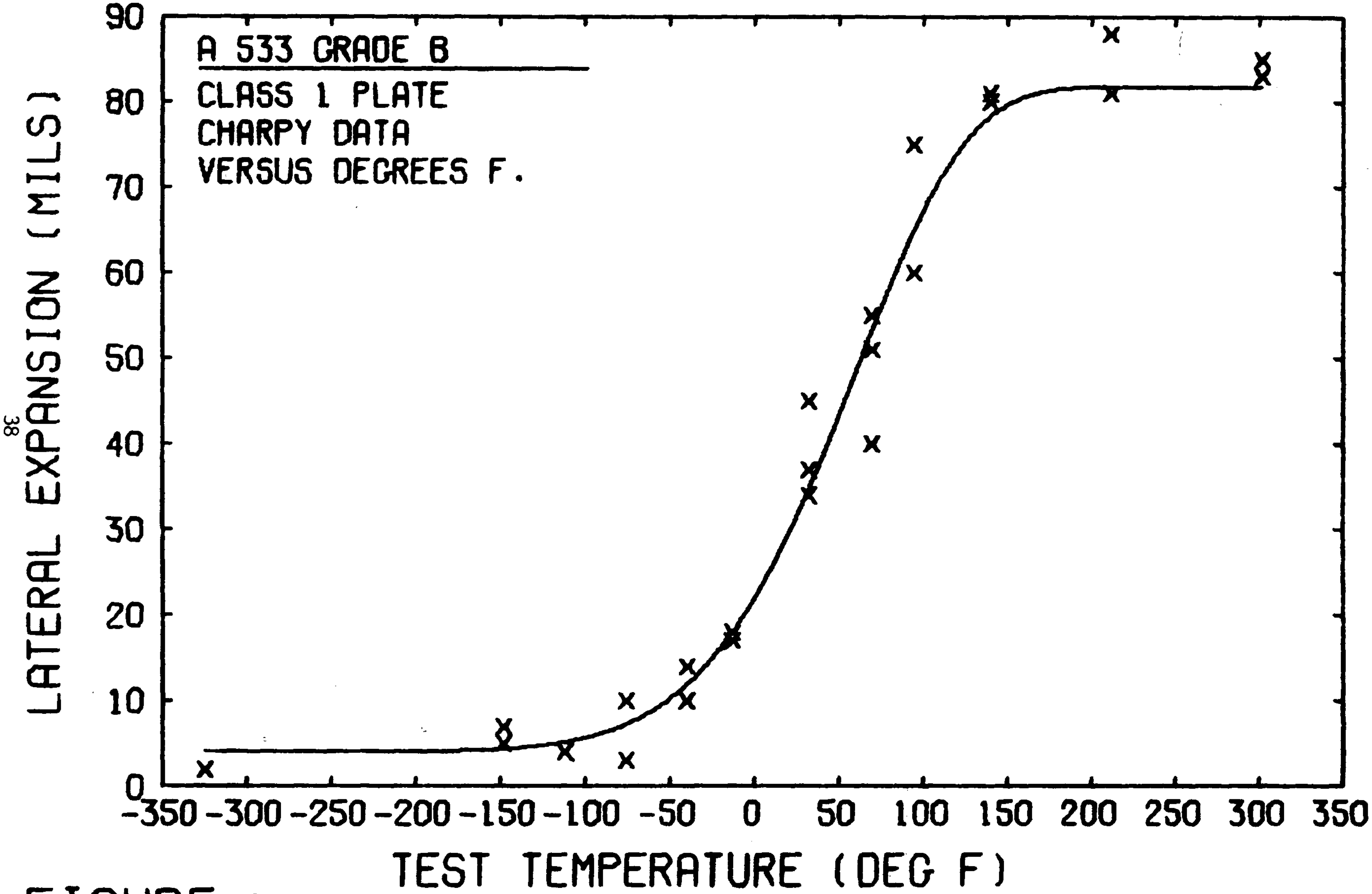

A 533 GRADE B
CLASS 1 PLATE
CHARPY DATA
VERSUS DEGREES F.
LATERAL EXPANSION (MILS)
0
10
20
30
40
50
60
70
80
90
-350 -300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350
TEST TEMPERATURE (DEG F)

FIGURE 8a

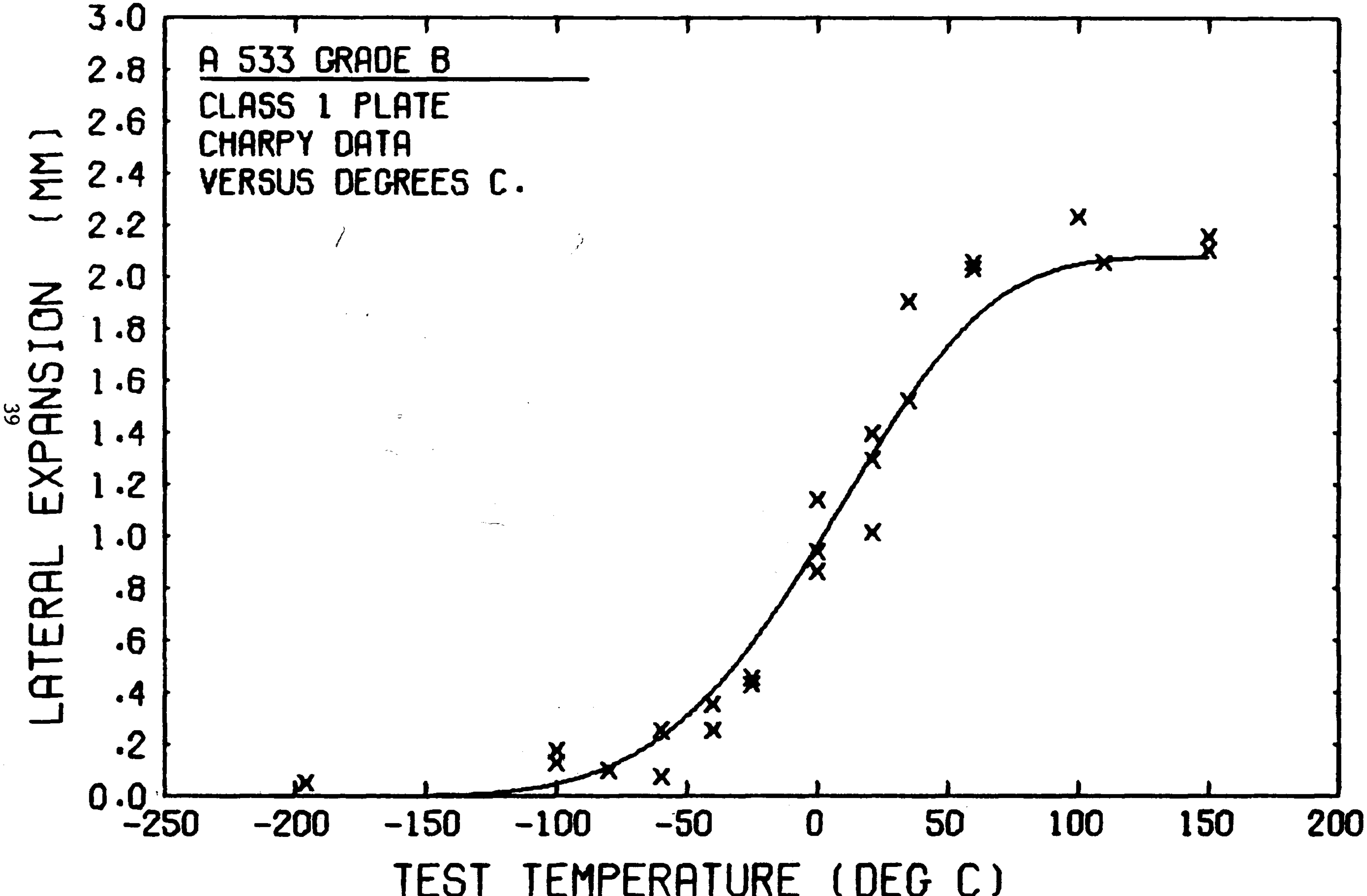

A 533 GRADE B
CLASS 1 PLATE
CHARPY DATA
VERSUS DEGREES C.
LATERAL EXPANSION (MM)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.0
-250
-200
-150
-100
-50
0
50
100
150
200
TEST TEMPERATURE (DEG C)

FIGURE 8b

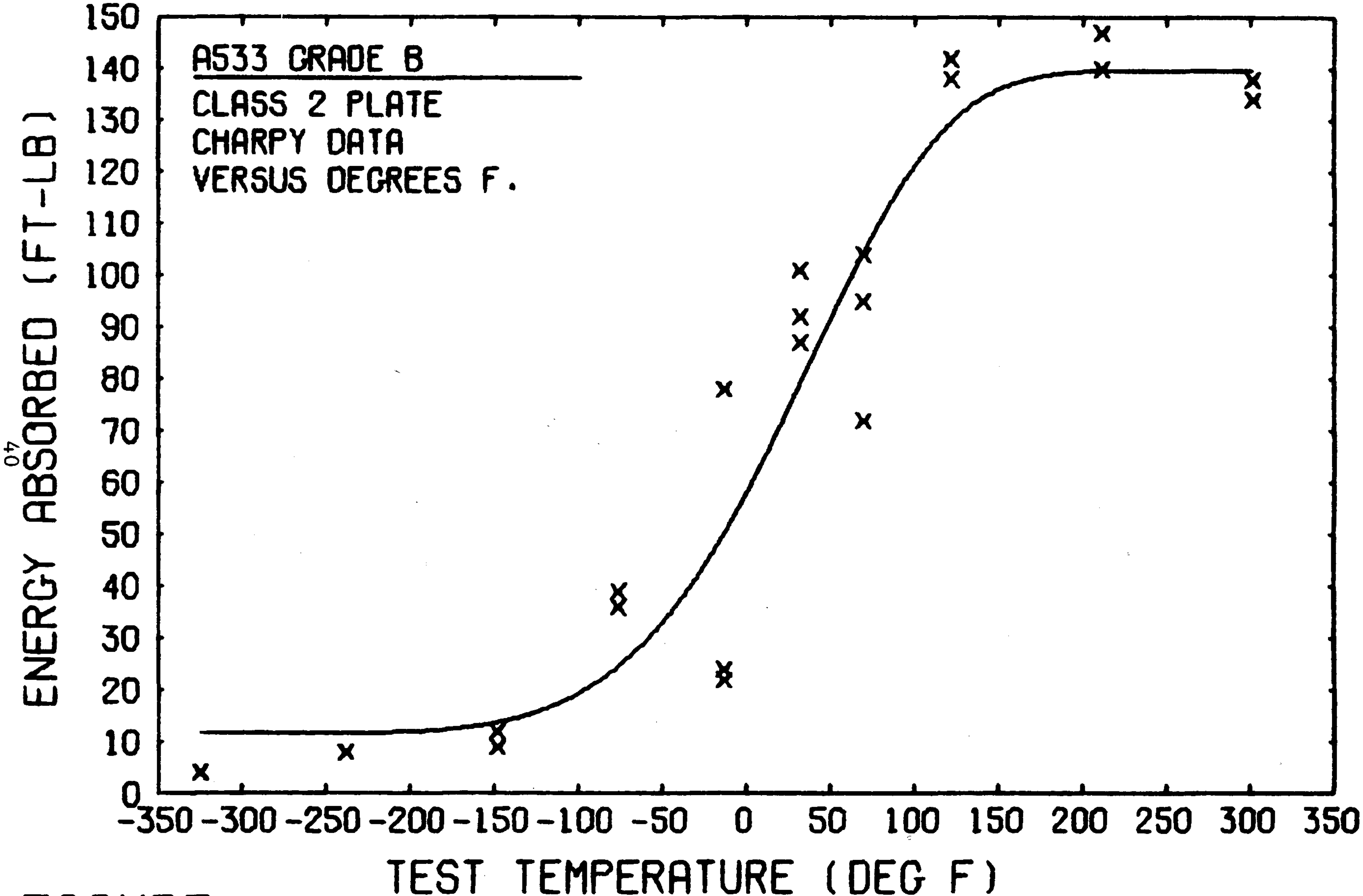

A533 GRADE B
CLASS 2 PLATE
CHARPY DATA
VERSUS DEGREES F.
ENERGY ABSORBED (FT-LB)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-350 -300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350
TEST TEMPERATURE (DEG F)

FIGURE 9a

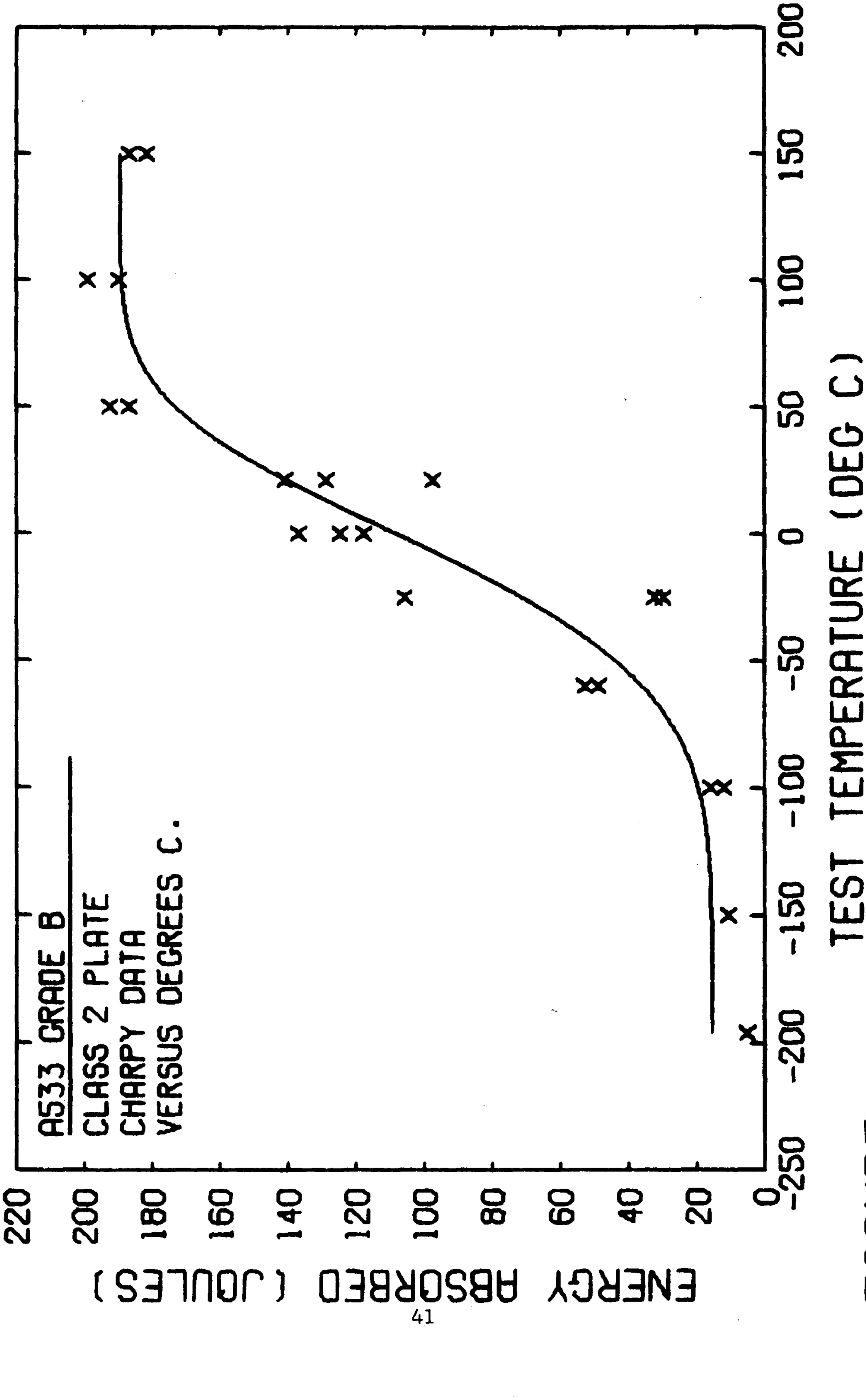

A533 GRADE B
CLASS 2 PLATE
CHARPY DATA
VERSUS DEGREES C.
ENERGY ABSORBED (JOULES)
TEST TEMPERATURE (DEG C)
0
20
40
60
80
100
120
140
160
180
200
220
-250
-200
-150
-100
-50
0
50
100
150
200

FIGURE 9b

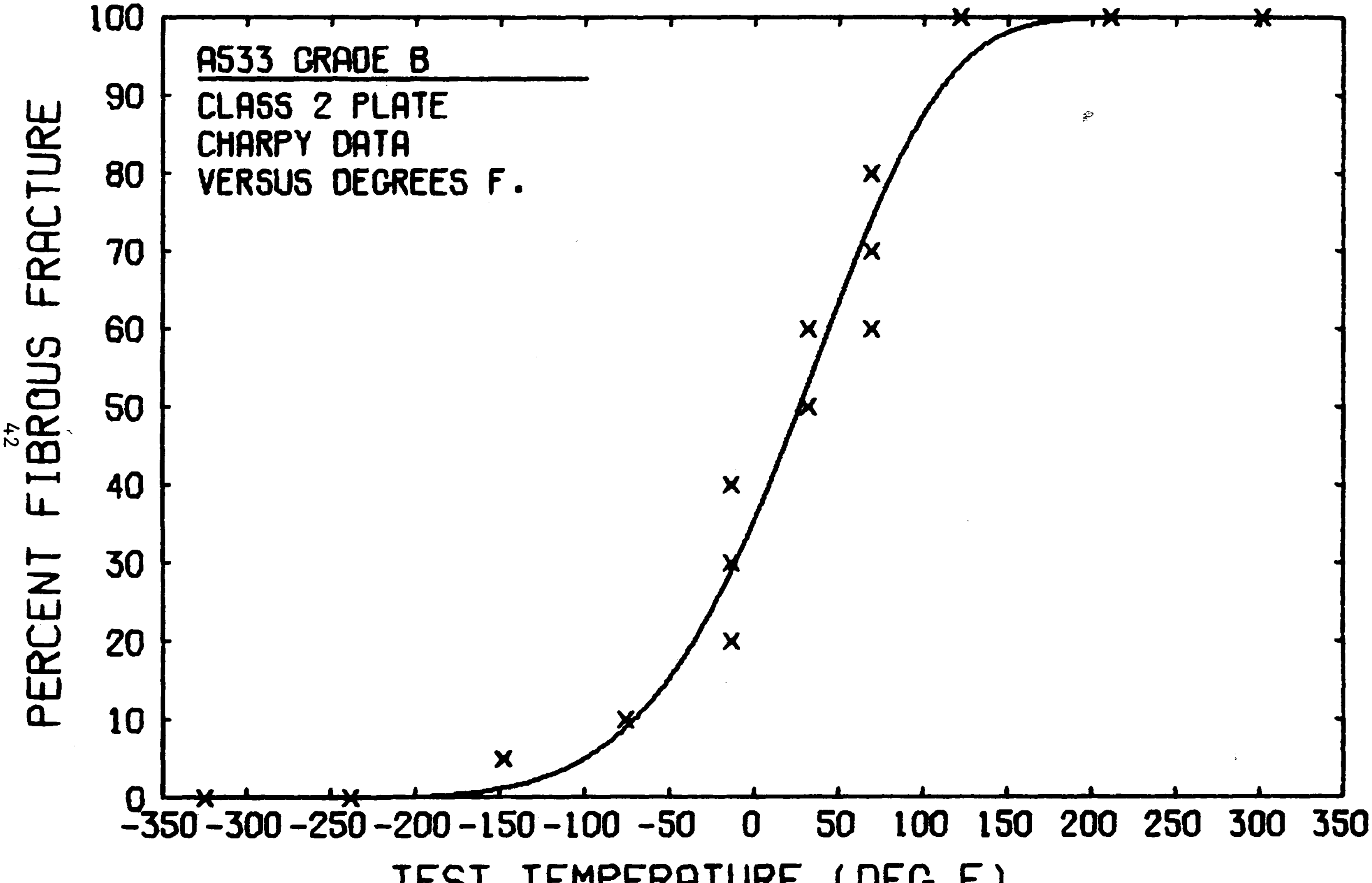

A533 GRADE B
CLASS 2 PLATE
CHARPY DATA
VERSUS DEGREES F.
PERCENT FIBROUS FRACTURE
100
90
80
70
60
50
40
30
20
10
0
-350 -300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350
TEST TEMPERATURE (DEG F)

FIGURE 10a

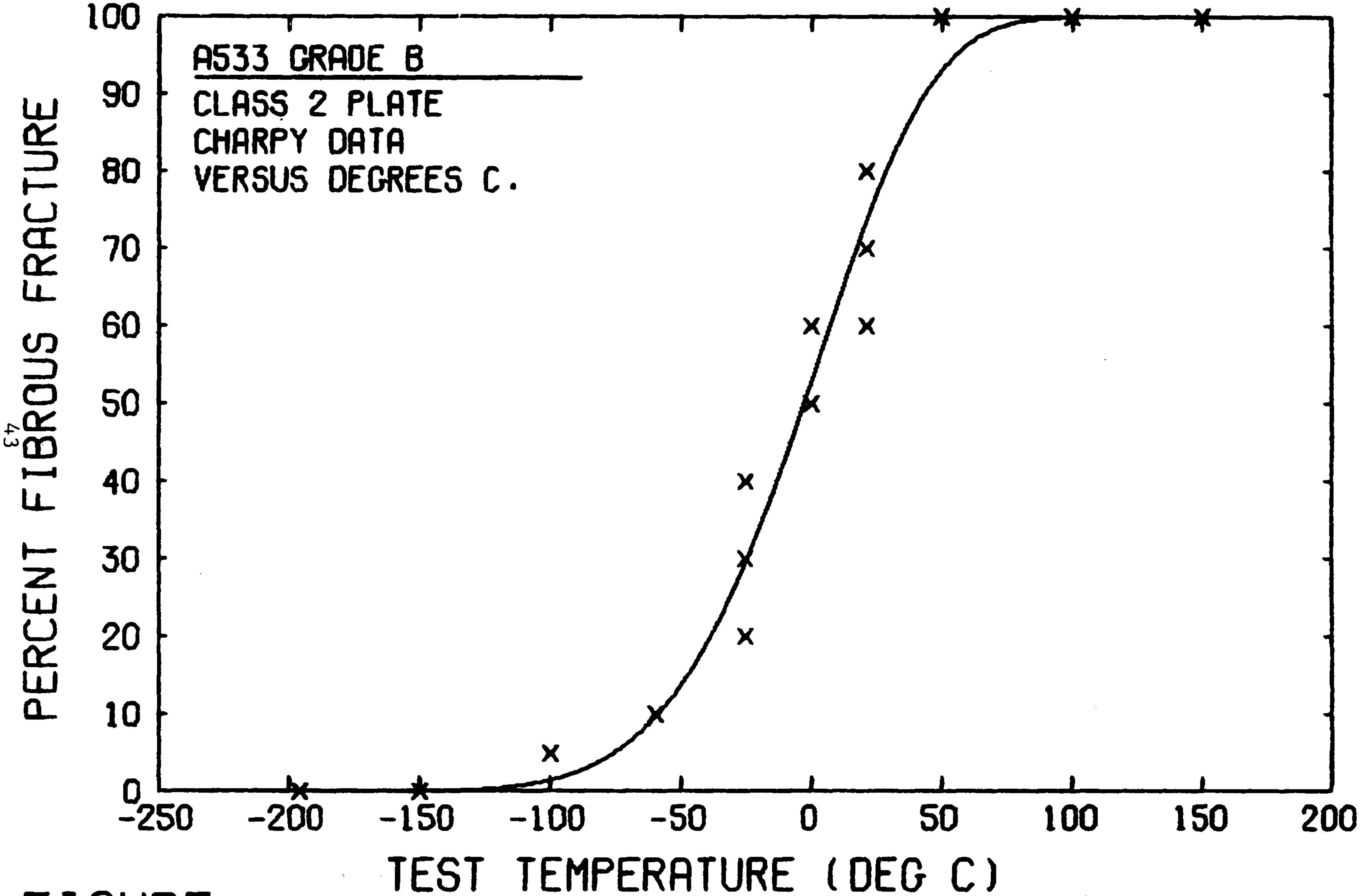

A533 GRADE B
CLASS 2 PLATE
CHARPY DATA
VERSUS DEGREES C.
PERCENT FIBROUS FRACTURE
0
10
20
30
40
50
60
70
80
90
100
-250
-200
-150
-100
-50
0
50
100
150
200
TEST TEMPERATURE (DEG C)

FIGURE 10b

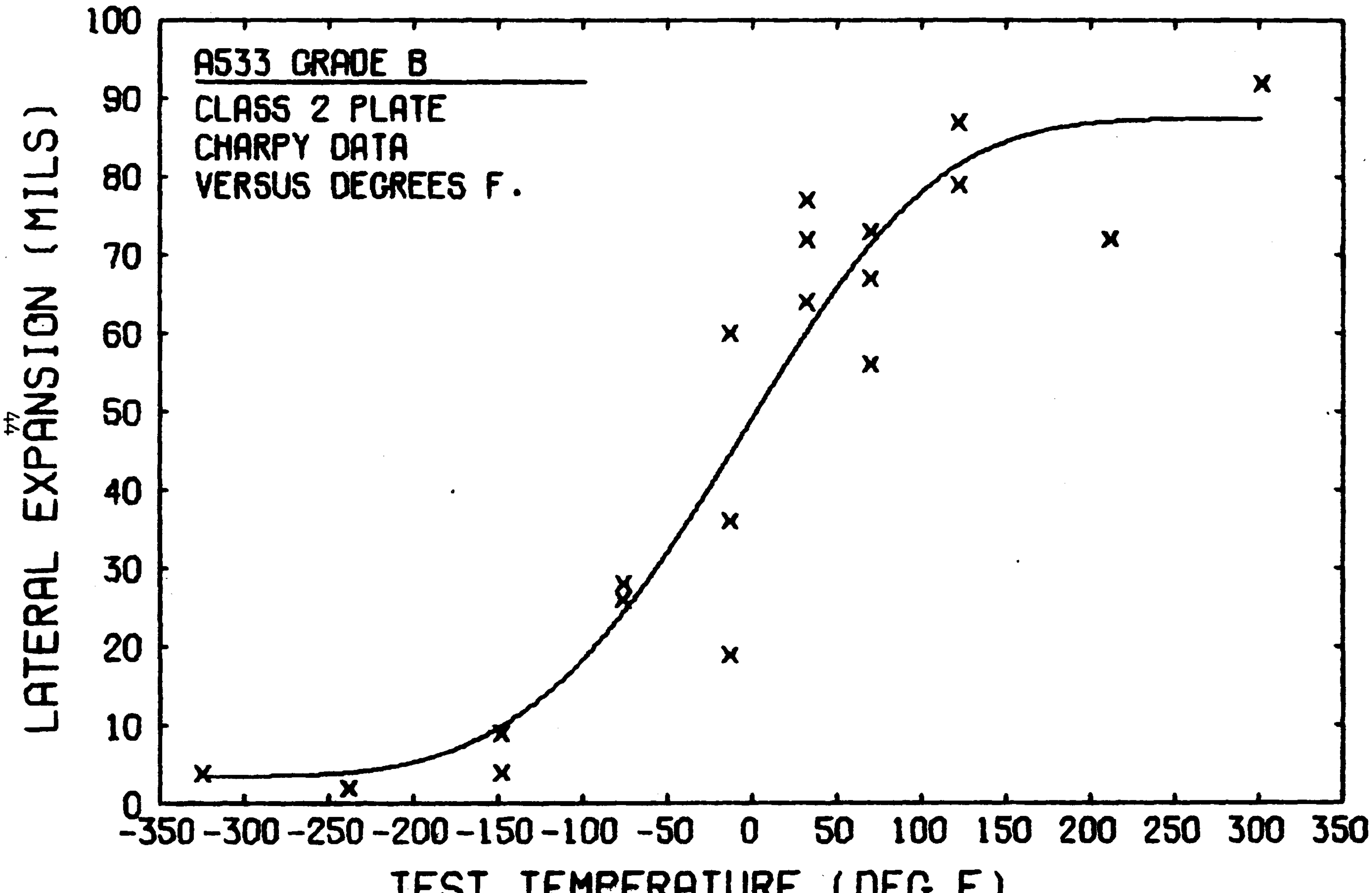

A533 GRADE B
CLASS 2 PLATE
CHARPY DATA
VERSUS DEGREES F.
LATERAL EXPANSION (MILS)
100
90
80
70
60
50
40
30
20
10
0
-350 -300 -250 -200 -150 -100 -50 0 50 100 150 200 250 300 350
TEST TEMPERATURE (DEG F)

FIGURE 11a

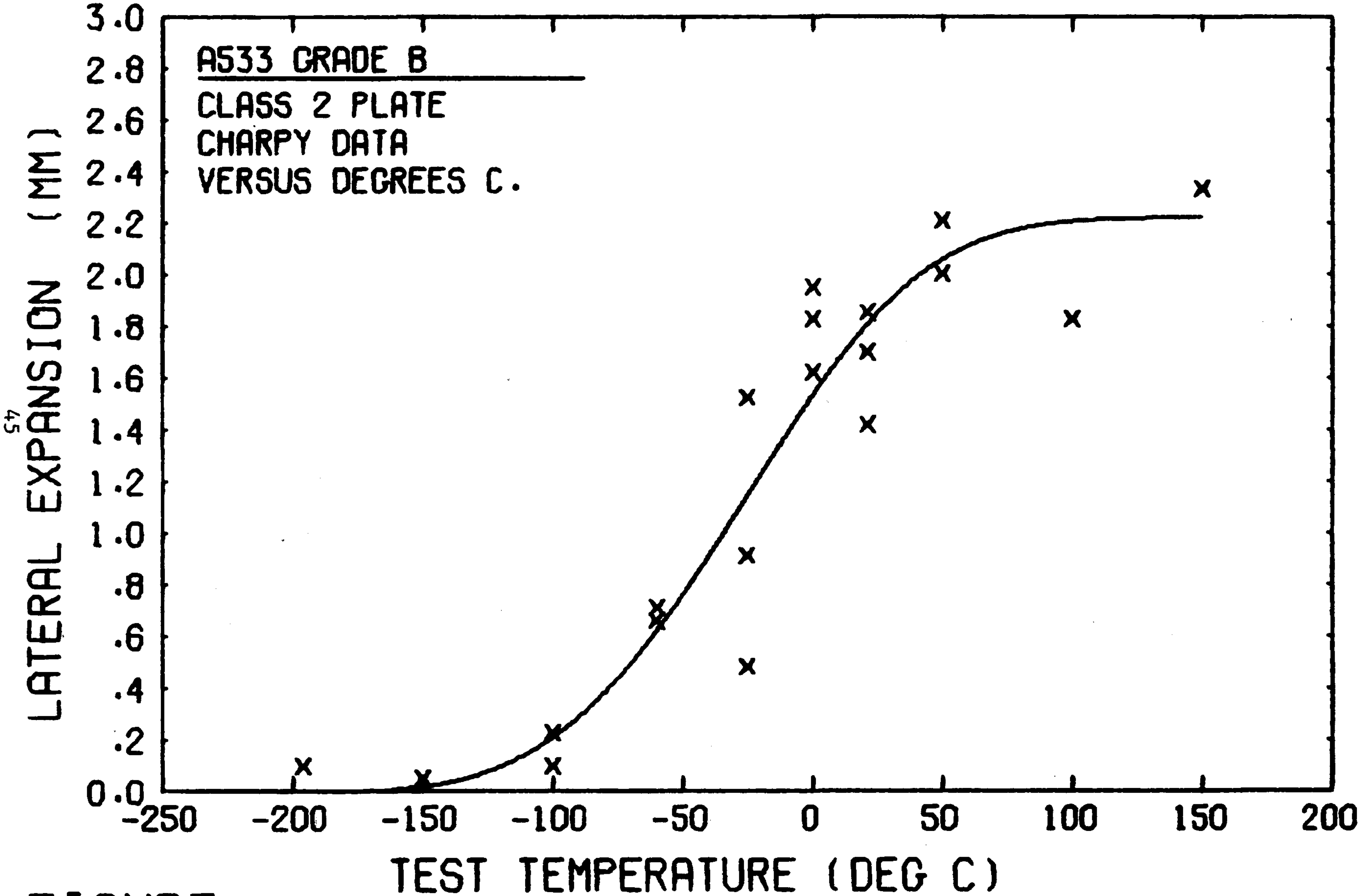

A533 GRADE B
CLASS 2 PLATE
CHARPY DATA
VERSUS DEGREES C.
LATERAL EXPANSION (MM)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.0
-250
-200
-150
-100
-50
0
50
100
150
200
TEST TEMPERATURE (DEG C)

FIGURE 11b

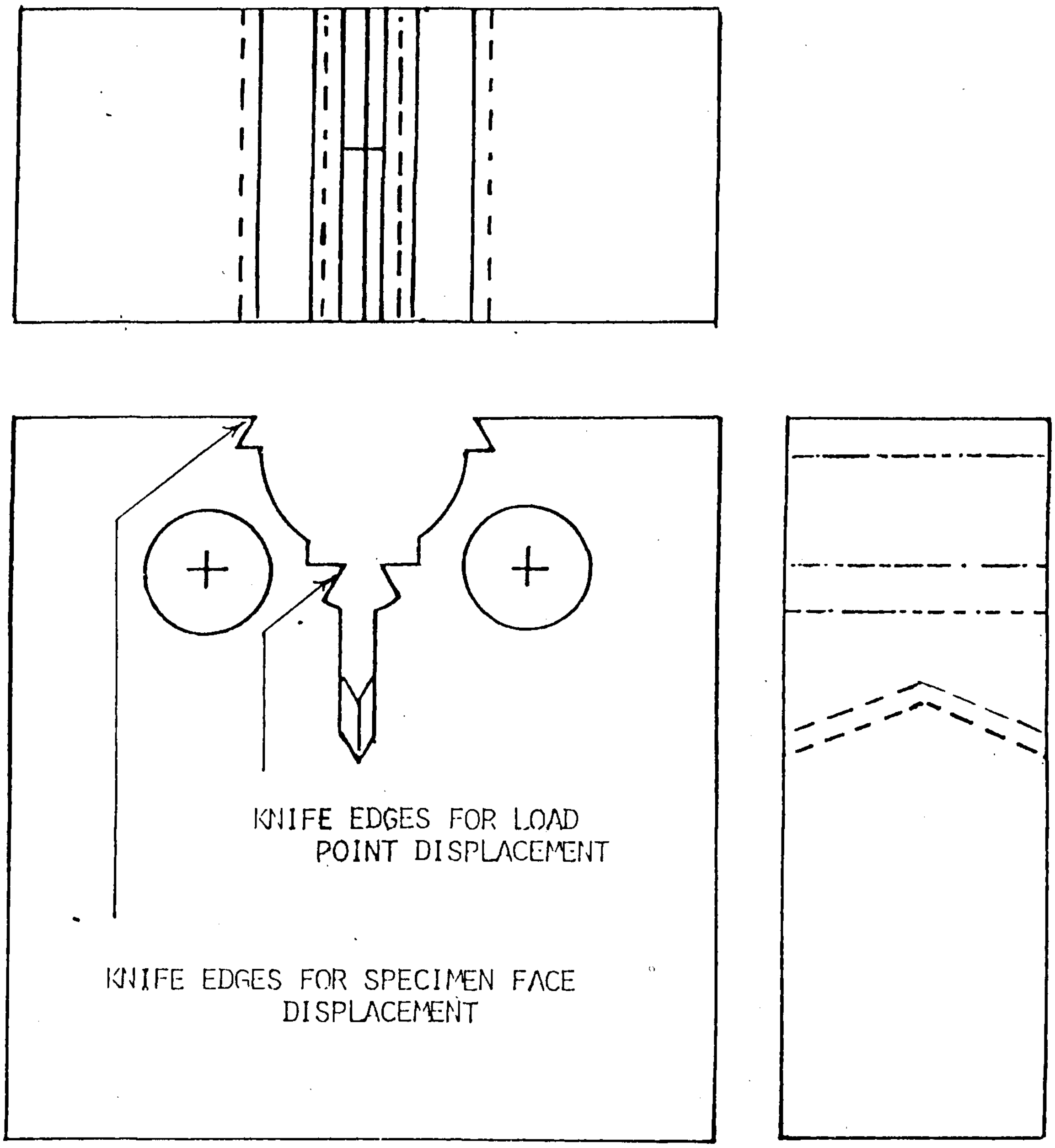


Figure 12 Modification to Compact Tension Specimen

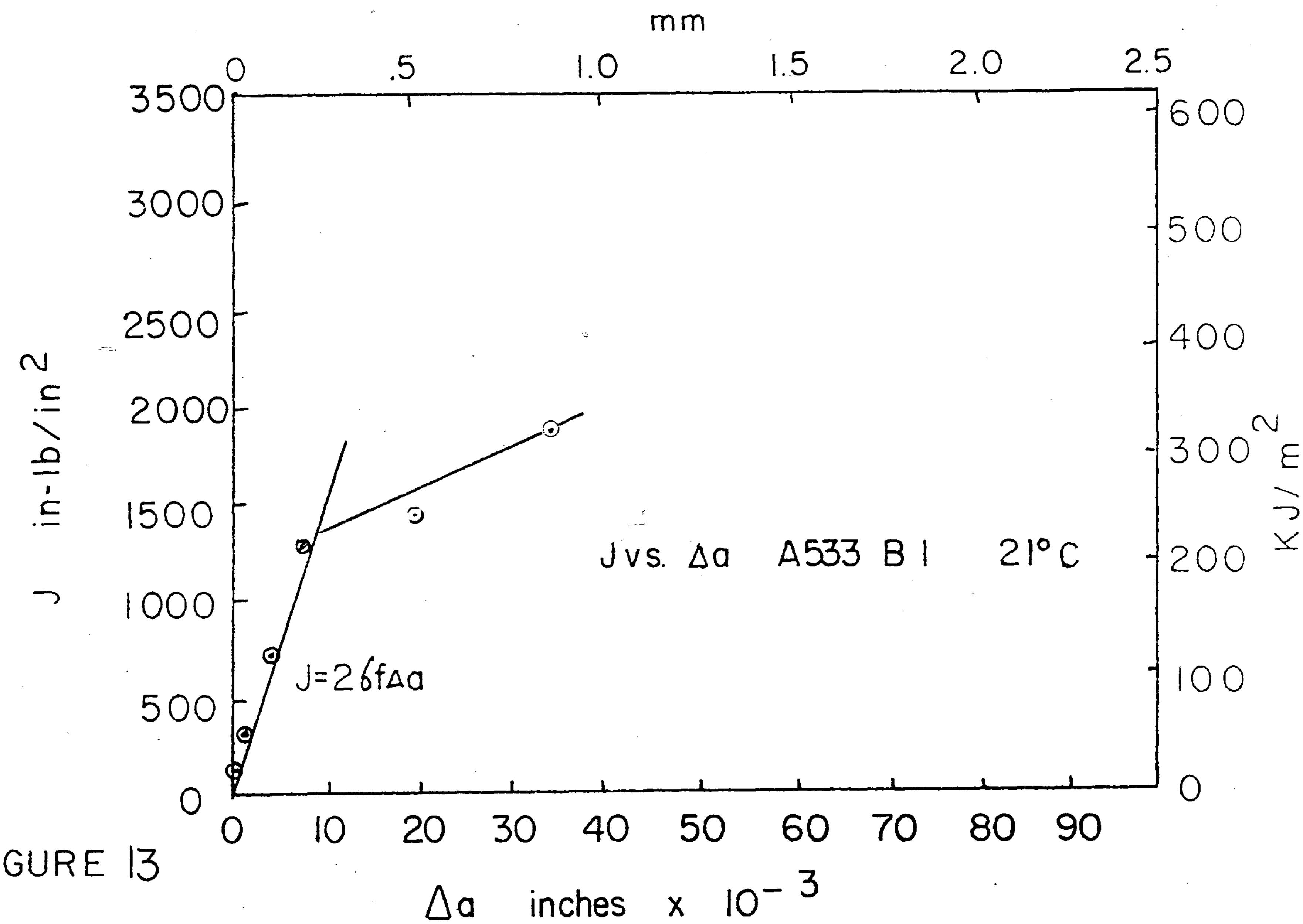

mm
0
.5
1.0
1.5
2.0
2.5
3500
3000
2500
2000
1500
1000
500
0
J in-lb/in2
600
500
400
300
200
100
0
KJ/m2
J=2σfΔa
J vs. Δa A533 B1 21°C
0
10
20
30
40
50
60
70
80
90
Δa inches x 10-3

FIGURE 13

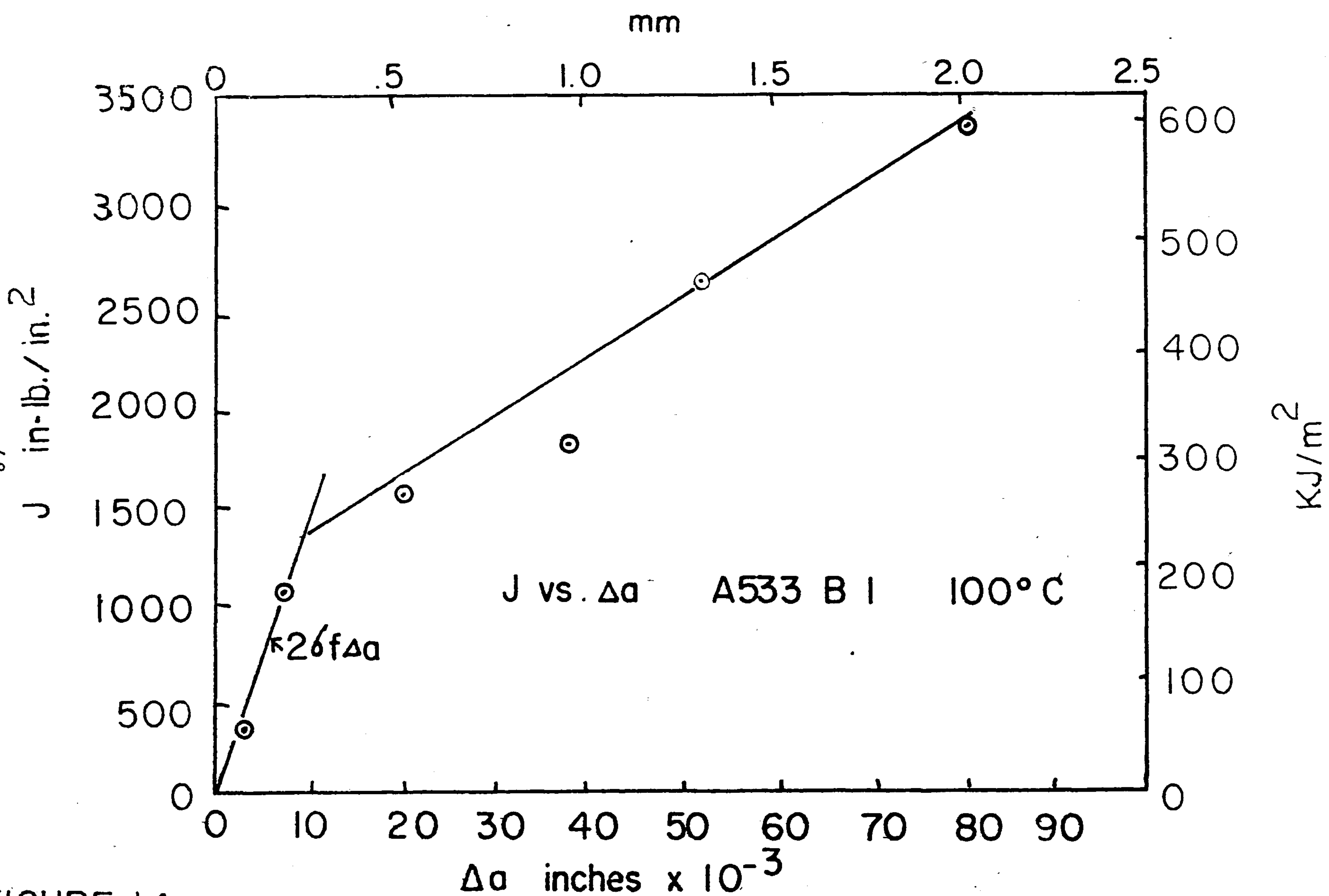

mm
0
.5
1.0
1.5
2.0
2.5
3500
3000
2500
2000
1500
1000
500
0
J in-lb./in.^{2}
600
500
400
300
200
100
0
KJ/m^2
0
10
20
30
40
50
60
70
80
90
Δa inches x 10^{-3}
J vs. Δa A533 B I 100°C
2σf Δa

FIGURE 14

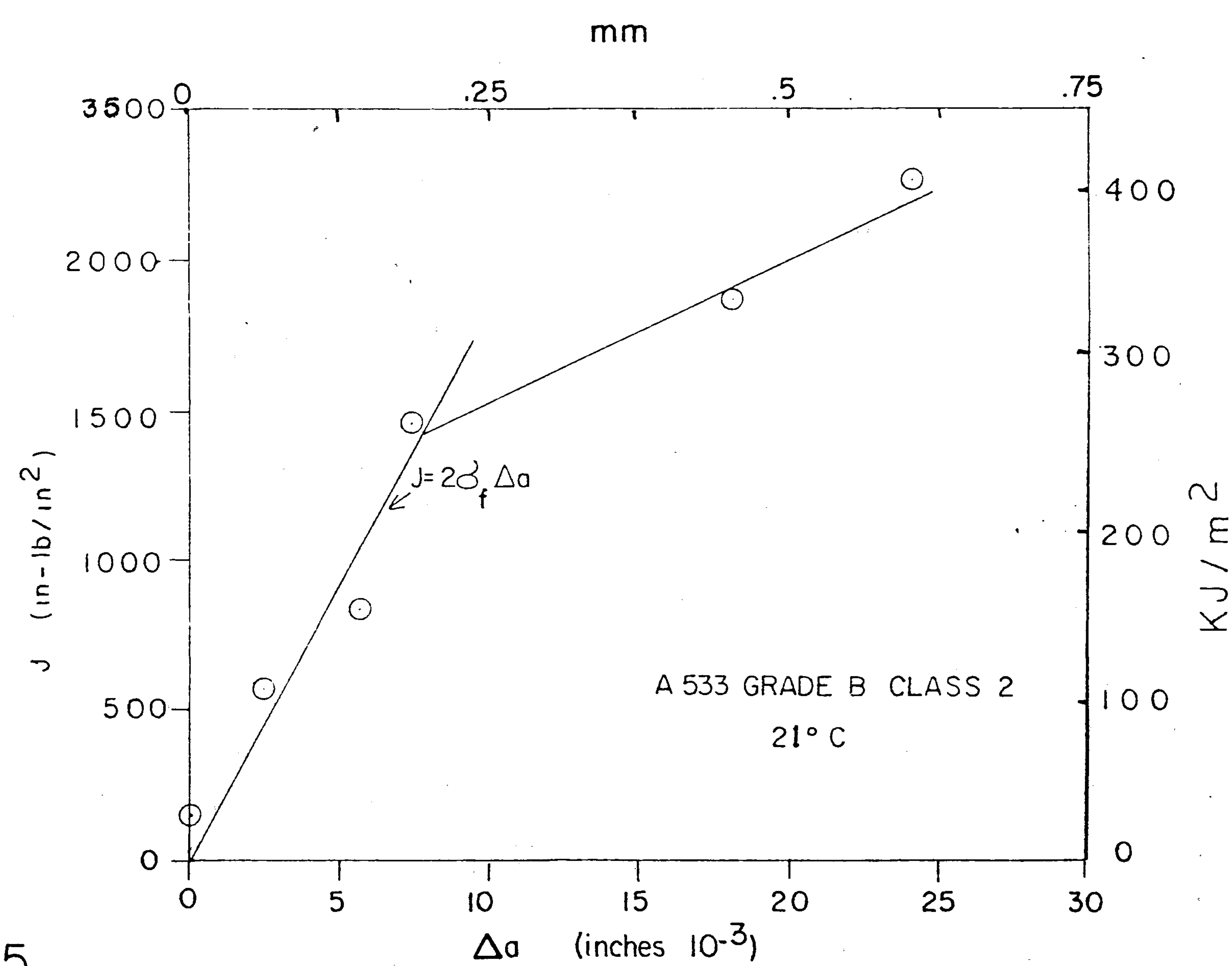

mm
0
.25
.5
.75
3500
2000
1500
1000
500
0
J (in-lb/in²)
400
300
200
100
0
KJ/m²
J=2γf Δa
A 533 GRADE B CLASS 2
21° C
0
5
10
15
20
25
30
Δa (inches 10-3)

FIGURE 15

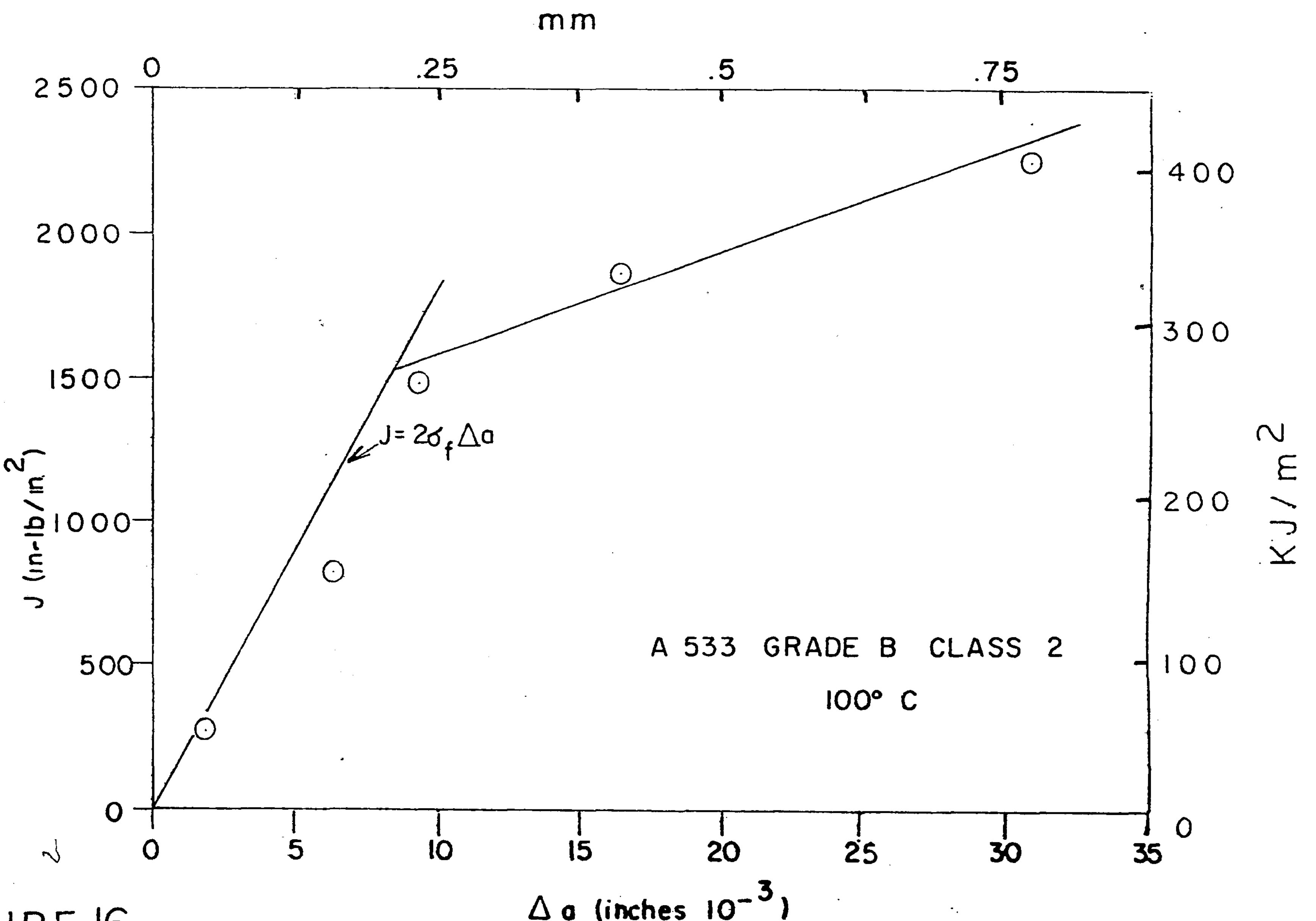
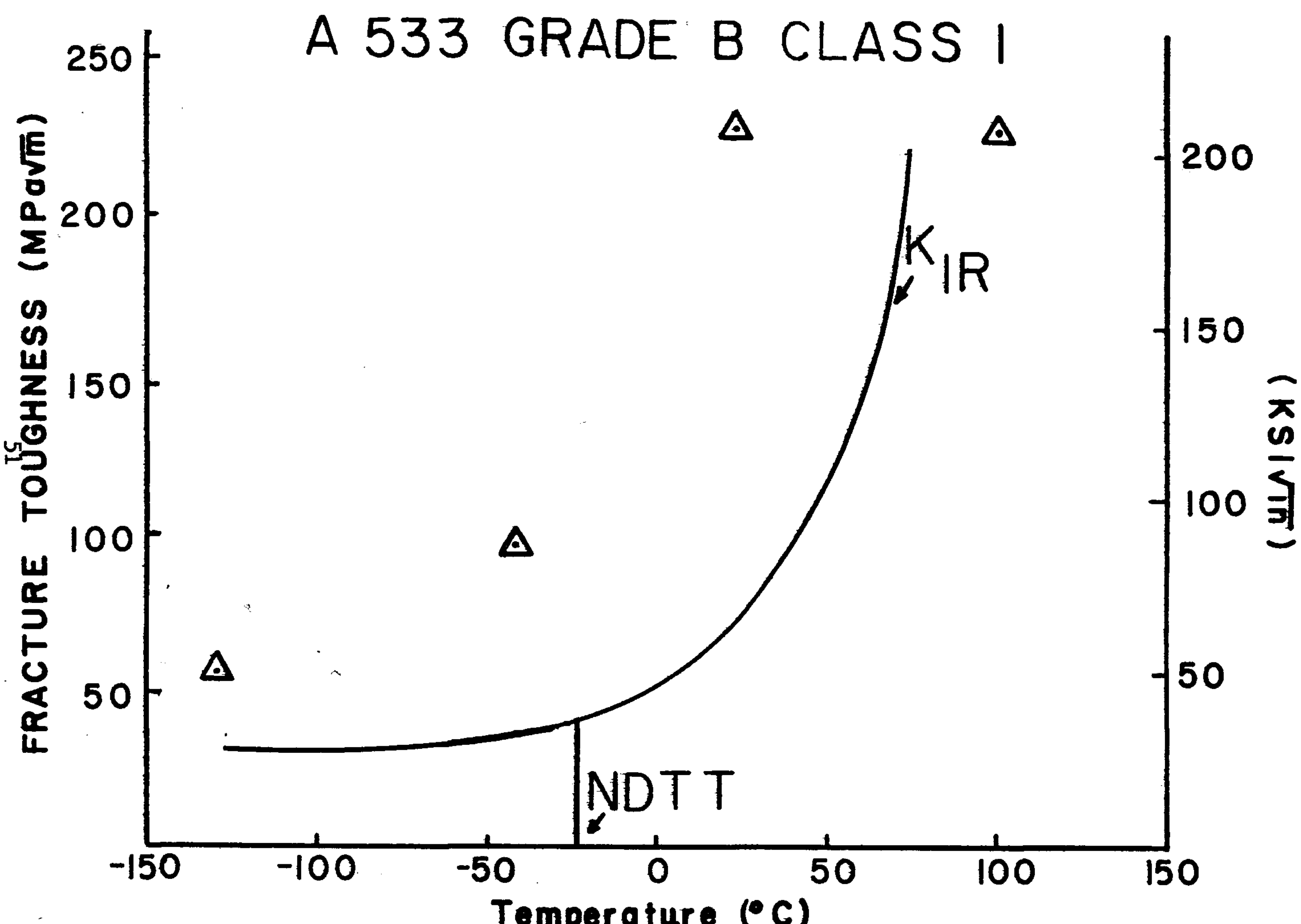
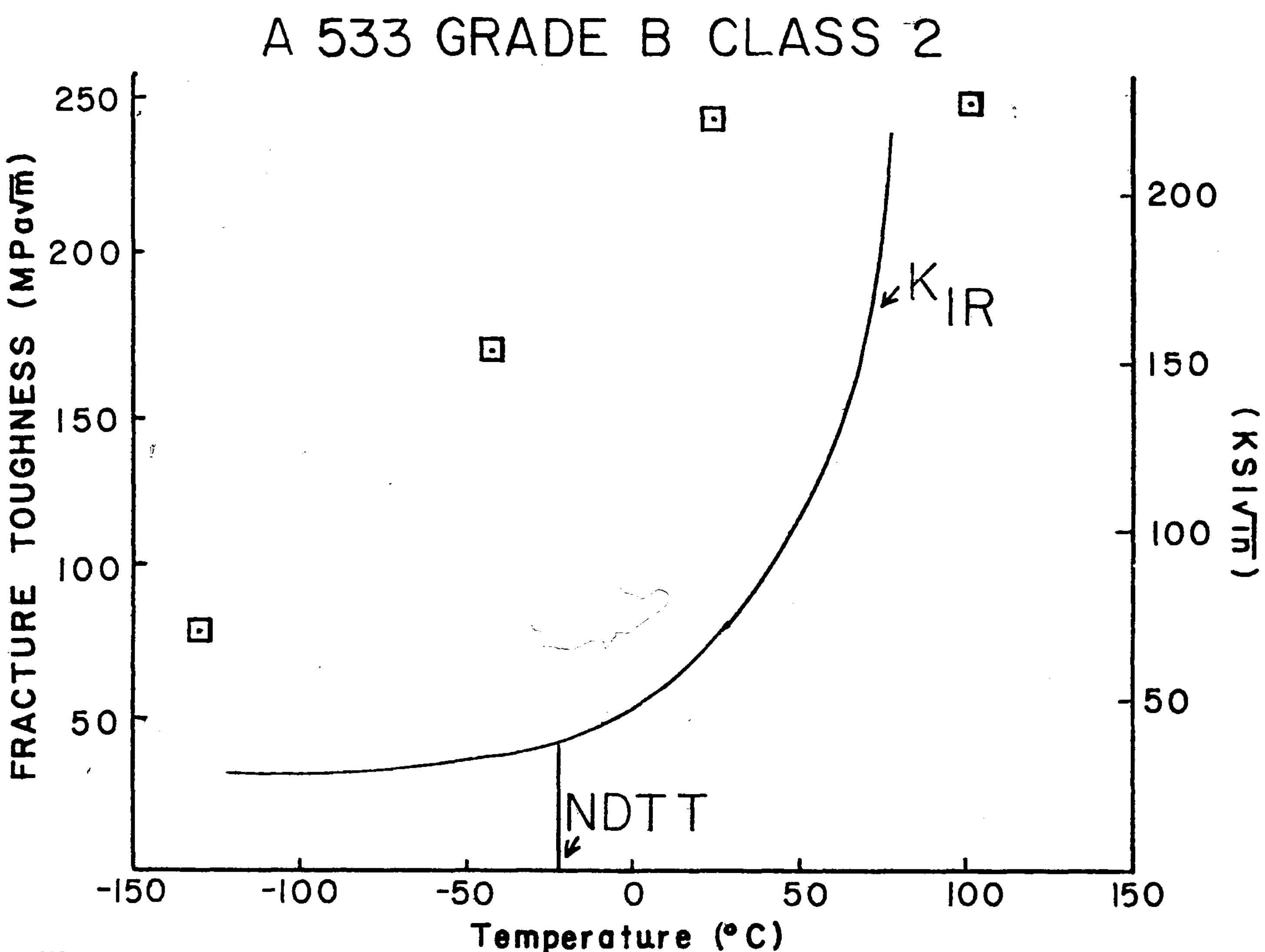

mm
0
.25
.5
.75
2500
2000
1500
1000
500
0
J (in-lb/in^2)
400
300
200
100
0
KJ/m^2
0
5
10
15
20
25
30
35
Δ a (inches 10^{-3})
$J = 2\sigma_f \Delta a$
A 533 GRADE B CLASS 2
100° C

FIGURE 16.



Fracture Toughness as a Function of Temperature

Fig. 17



Fracture Toughness as a Function of Temperature
Fig. 18

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3. J. R. Rice, "A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks," J. of Appl. Mech., 35, (1968), p. 379.

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6. C. C. Veerman and T. Muller, "The Location of the Apparent Rotation Axis in Notched Bend Testing," Experimental Fracture Mechanics, Vol. 4, (1972), pp. 25-32.

7. B. Gross, E. Roberts, and J. E. Strawley, "Elastic Displacements for Various Edge Cracked Plate Specimens," International Journal of Fracture Mechanics, Vol. 4, No. 3, (1968).

8. J. D. Landes, and J. A. Begley, "Test Results from J-Integral Studies: An Attempt to Establish a J_{IC} Testing Procedure," Fracture Analysis, ASTM STP 560, ASTM, (1974), pp. 170-186.

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