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Defect Characterization and Dimensioning of Cracks in Welds by the Ultrasonic Diffraction Method

S Golan

Office of Nondestructive Evaluation
National Measurement Laboratory
National Bureau of Standards
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DEFECT CHARACTERIZATION AND DIMENSIONING OF CRACKS IN WELDS BY THE ULTRASONIC DIFFRACTION METHOD

by

S. Golan*

ABSTRACT

The possibility of applying an ultrasonic diffraction method for dimensioning of crack-like defects in welds was investigated. A feasibility study was carried out and optimum test conditions were established using a series of test specimens with narrow slits. A series of welded specimens with in-welded cracks were tested. The possibility of using a quantitative diffraction technique for nondestructive examination of pipeline welds in field conditions is discussed.

INTRODUCTION

With the conventional ultrasonic pulse-echo technique, flaw size is related to echo-amplitude. Amplitude, however, being strongly affected by many factors[1], is rather insensitive to size. Consequently, the pulse-echo technique is not suitable for quantitative measurements. In welds, quantitative evaluation becomes even more complicated by the anisotropy and inhomogeneity inherent in welded materials and by geometric factors. The inability of the pulse-echo technique, which is based on reflectivity, to serve as a quantitative tool provided the impetus for development of techniques based on other phenomena of interaction between the flaw and the acoustic field, such as scattering, diffraction, interference, etc. It seems that the most promising technique to develop into a practical and economical quantitative testing tool for field work is the diffraction technique.[1-6] Figure 1 shows an example of ultrasonic sizing of slits. More such curves are given in reference 1. It is especially useful for dimensioning of crack-like defects. This technique has three main advantages over some other emerging techniques: flaw size is computed using only time measurements, which can be made more accurate and more reliable than amplitude measurements; conventional pulse-echo equipment can be used; and operators familiar with the pulse-echo technique can easily adopt the diffraction technique.

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* Permanent address, Israel Institute of Metals, Israel. This report was prepared while the author was on a temporary assignment to the NBS Office of Nondestructive Evaluation.

BASICS OF THE DIFFRACTION TECHNIQUE

When an ultrasonic wave impinges on the tip of a crack, waves of shear (s) and compressional (P) modes are scattered from the tip in a circular form. Figure 2 shows a photoelastic pattern of the scattered acoustic field from the tip of a narrow slit in a glass block. From the time interval between the entering of the incident wave and emerging of the tip-diffracted wave the depth of the tip can be computed.[1-5] Most reliable results are obtained when time delay is measured from a conveniently chosen reference signal. Figure 3 shows a diffraction triangle formed by the transmitted, the diffracted and a compressional surface wave which serves as reference.[1] Equation 1 gives the relationship between time delay and depth of the tip when a P surface wave is used as a reference.

$$C_2^2 - C_1^2 Y^2 + 4\cos\alpha\left[C_1(\Delta+1) - C_2^2 (\sin\alpha) Y\right] - 4\cos^2\alpha\left[(\Delta+1)^2 - C_2^2\right] = 0 \quad (1)$$

α - Angle of incident beam

C_1, C_2 - Mode coefficients for impinging and diffracted beams

$C = 1$ - For a compressional beam

$C = \frac{V_c}{V_s}$ - For a shear beam

V_s - Shear wave velocity

V_c - Compressional wave velocity

$Y = \frac{y}{a}$ - Depth of source of diffraction; nondimensional

$\Delta = \frac{\delta}{a}$ - Depth of source of diffraction; nondimensional

2δ - Time delay expressed in units of length

$2a$ - Distance between transducers

y - Depth of source of diffraction.

From this general equation specific equations can be derived for different modes of transmitted and diffracted waves and for various diffraction triangles.[1,2] If the reference signal is a bottom reflection and the diffracted and reference signals are maximized (see Figure 4), the relationship between time-delay and depth for a single or double transducer technique is given in Equation 2.

$$y = T - \delta\cos\alpha \tag{2}$$

T - thickness of material.

OPTIMUM CONDITIONS FOR DIMENSIONING OF CRACKS

The diffraction techniques can be used to dimension cracks open to the front or back surfaces as well as internal cracks, provided a tip-diffracted signal can be detected. This, however, is quite often very difficult. The tip-diffracted wave usually has a low amplitude, and high amplification is necessary to reveal the signal. This, in turn, forms a noisy background which might blur the tip signal. The noise signals come from various sources; scattering from grains and inclusions, mode conversion, scattering from the crack surface, back wall reflection, surface waves, side loops, internal reflections from the wedge, and electronic noise. Figure 5 shows a typical oscilloscopic trace in the background of a signal diffracted from the tip of a fatigue crack.[5] The crack depth can be sized with sufficient accuracy and reliability only if the tip diffracted signal can be clearly detected and unambiguously identified among the spurious signals. As has been shown in this and some other works[1-5] under certain conditions signal-to-noise ratio can be considerably improved and the tip signal can be detected. By analyzing the oscilloscopic trace, the tip signal can be in many cases identified.[5,6]

Three parameters determine the detectability of a signal; amplitude, resolution, and dynamic response. Dynamic response is defined as the drop in amplitude caused by displacing the transducer from its maximum amplitude position (see Figure 6). When the dynamic response is high, a sharp drop in amplitude will be observed when the transducer is slightly displaced. This parameter is a very strong crack indicator.

All three parameters are mode and angle dependent. On a goniometer the angle-amplitude dependence was determined for the PP mode (incident and diffracted waves of the compressional mode)[1]. It was found that maximum amplitude is obtained when the angle between the transducers approaches 180° ($\alpha \to 90°$).

In former works[1-4,6] the PP mode was primarily used in order to prevent interfering signals of the P mode. In later work[6] it was found that, by using the SS mode and angles α in the range of 40° to 50°, higher amplitudes are obtained. The dynamic response is higher[6] because of the smaller angles and, because of the lower velocity of shear waves, resolution is almost doubled. By choosing an angle between 40° and 50° interfering compressional mode signals do not appear. An additional improvement in amplitude is achieved by using one instead of two transducers. This has additional advantages: it is more convenient to handle one transducer; no alignment between the transducers is necessary; and the dead zone is smaller, as it is not limited by wedge geometry.[6] The high amplitude noise which appears when one transducer is used can be minimized by chosing a wedge which filters out the internal reflections.[7]

SIZING OF SIMULATED CRACKS IN WELDS

For the feasibility study a series of specimens with a simulated internal crack in welds was prepared. The "inwelded crack" was formed by incomplete penetration of a butt weld. The location, size and orientation of the "crack" was controlled by the bevel geometry of the welded plates (see Figure 7, 8 and 9). In order to achieve minimum crack width (0.00 to 0.06 mm), minimum deformation and, as closely as possible, a straight line of the tip, the plates were welded and cooled to room temperature while clamped in a fixture. The material used was 25.4-mm low-carbon steel plates. Specimens of 22-mm width were cut from the welded plates. The specimens were machined, polished and etched to reveal the "crack" and the weld cross section. In order to check the ability of the diffraction method to dimension normal as well as inclined internal cracks in the as-welded condition, four types of specimens were prepared: as-welded with normal "cracks"; machined to remove the excess of the welding, with normal "cracks"; and as-welded and machined with 45° "cracks" (see Figures 8 and 9). Measurements were made with the two-transducer technique, 45° 5-MHz shear waves, equilateral diffraction triangle, and a back-wall reflection signal as reference. (The 45° angle is within the range of good detectability). Because of the many advantages of the one-transducer technique an initial attempt was made to employ it. This technique was, however, abandoned because of high-amplitude interfering signals reflected from the "crack" surface (see discussion below).

The setup and the transducer arrangement are shown in Figures 10 and 11. Measurements were taken after the amplitude was maximized by slight lateral movements of the transducers. Results were verified by measurements from four different transducer locations, with direct and double-skip beams (see Figure 12), and from both sides of the specimen. In Table 1 a schematic presentation of the different beam paths and direct and ultrasonic measurement results are given in x,y coordinates. The coordinate system is shown in Figure 8. The x coordinate was determined from the positions of the transducers. The scatter of the x measurements was within ±2mm. The x data are arithmetic averages of five measurements. In Figure 13 values of depth (y coordinate) made by direct and by ultrasonic measurements are compared. The differences are not necessarily deviations but, perhaps, true differences in the depth of the tip at the outer surface (measured directly) and at the middle of the specimen (measured ultrasonically).

DISCUSSION

Although it was shown in several works[1-5] that accurate and reliable sizing of cracks with the diffraction technique is feasible, testing of welds in materials less than 25 mm in thickness under field conditions presents special difficulties which have not yet been completely resolved. This can be seen in Table 1 where, in many places, measurements were not possible. Some of the difficulties are described below and schematically presented in Figure 14. Because of the coarser grains, the directional structure and the microimperfections usually present in weld material, the ultrasonic noise from the weld is more severe than in the parent material. This might be improved by using a lower frequency.

The advantage of using the one-transducer technique is obvious. This technique, however, might cause misleading results because of multiple reflections from the crack surface. Because of the crown of the weld, scanning of the weld with a direct beam is limited and often not possible and double-skip beam paths must be employed. This increases noise and attenuation.

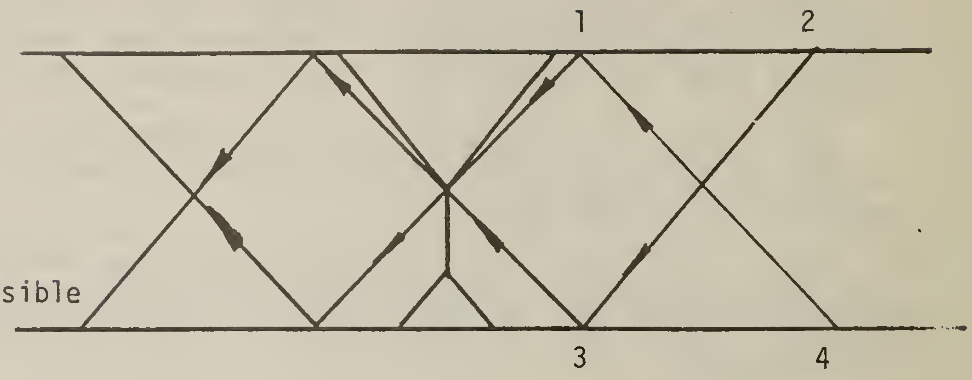
The high-amplitude back-wall reflection often masks the low-amplitude tip-diffracted signal and resolution becomes difficult and often impossible, especially in thinner material.

Some of the difficulties mentioned above might be diminished by changing testing parameters such as frequency, diffraction triangle, mode combination, transducer and wedges. Further investigation to diminish interfering factors is recommended.

Table 1

Ultrasonic Measurements

A - As welded specimens
B,C - Machined specimens
1,2 - Normal "cracks"
3 - 45° "cracks"
W - Weld imperfection
N - Measurement not possible (explained in text)



Specimen Number	Coordinate	Direct Measurement (mm)	Ultrasonic Measurements (mm)				
			I	II	III	IV	Average
1A	y	9.1	N	N	9.0	N	9
	x	0.5			1.0		1.0
	y	9.4	95	N	N	N	9.5
	x	0	0				0
	y	20.2	N	N	N	20.0	20.0
	x	0				0.5	0.5
	w-y	7.0	N	7.0	N	7.0	7.0
	x	-2.5		1.0		-1.0	0
1B	y	9.4	N	10.5	9.5	N	10.0
	x	0		-1.0	-1.5		-1.2
	y	20.1	20.8	20.4	N	20.5	20.6
	x	0	-1.5	0		0	-0.8

Table 1

Ultrasonic Measurements
(Continued)

Specimen Number	Coordinate	Direct Measurement (mm)	Ultrasonic Measurements (mm)				
			I	II	III	IV	Average
1C	y	9.6	N	8.8	9.1	9.5	9.1
	x	0		2.0	1.0	0	1.5
	y	18.8	19.7	N	N	19.0	19.4
	x	0	0.5			0.0	0.3
2A	y	12.1	N	12.0	N	11.5	11.7
	x	0		0		-0.5	-0.3
	y	18.4	N	N	N	N	N
	x	0					
2B	y	11.7	N	11.2	11.0	11.5	11.2
	x	0		0	0	0.5	0.2
	y	18.1	18.3	17.4	N	18.5	18.1
	x	0	-1.0	1.5		-0.5	0
2C	y	11.0	N	9.0	N	9.8	9.4
	x	0		1.0		1.5	1.2
	y	18.0	N	17.9	N	N	17.9
	x	0		0			0
	w-y	N	N	7.0	7.0	7.0	7.0
	x			3.0	2.5	3.5	3.0

Table 1

Ultrasonic Measurements
(Continued)

Specimen Number	Coordinate	Direct Measurement (mm)	Ultrasonic Measurements (mm)				
			I	II	III	IV	Average
3A	y	11.1	N	N	N	11.0	11.0
	x	0				0	0
	y	19.6	N	19.4	N	20.0	19.7
	x	-8.4		-8.5		-8.0	-8.3
	w-y	Several points from weld imperfections					
	x						
3C	y	11.4	10.6	10.7	11.5	10.7	10.9
	x	0	0	1.5	1.0	0	0.6
	y	18.8	18.7	N	N	18.5	18.6
	x	18.4	8.0			8.0	8.0

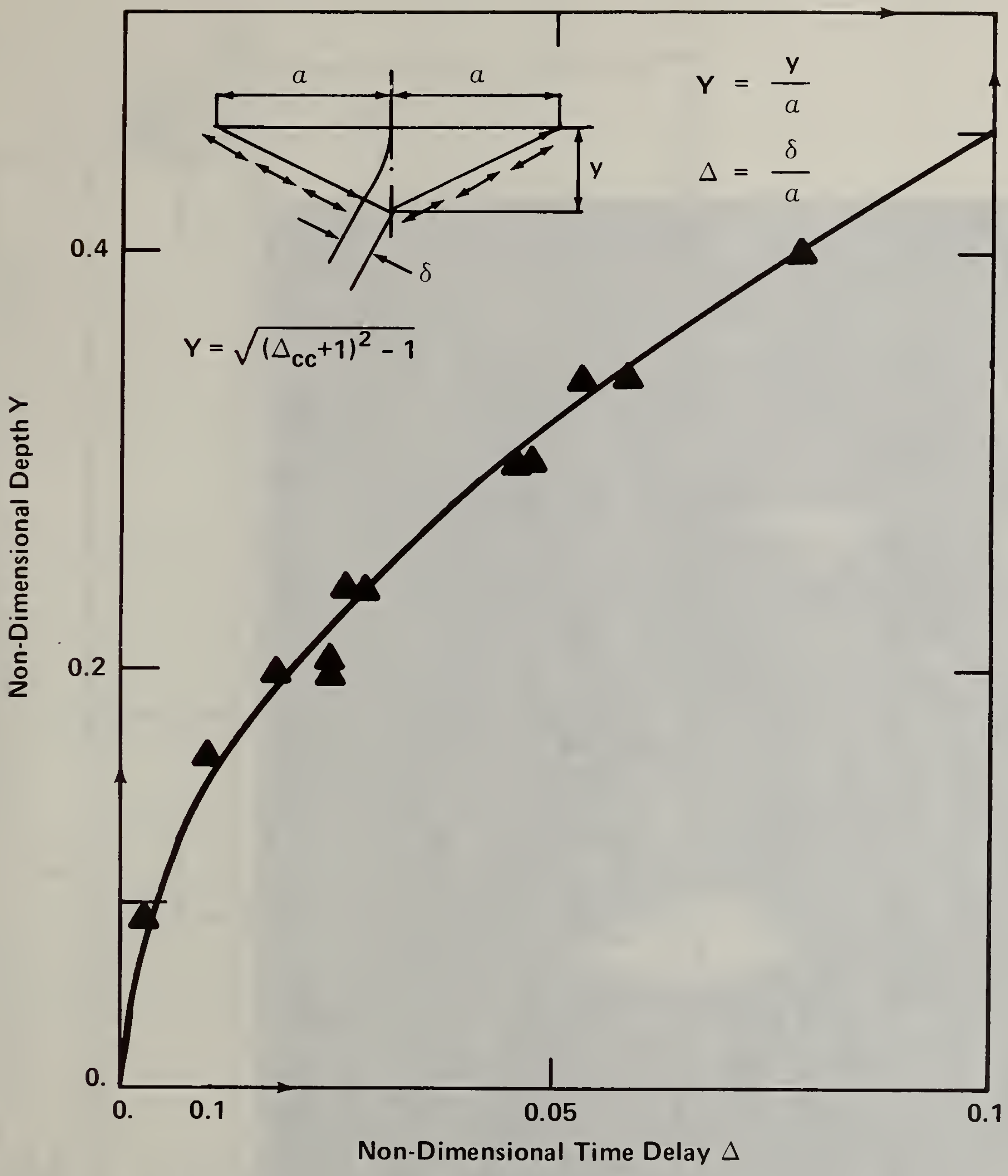


Figure 1. Sizing of Slits With The Double Transducer Technique - PP array (compressional impinging, compressional diffracted waves).

Figure 2. Photoelastic Visualization of P Waves (outer circles) and S Waves (inner circles) Diffracted From A Tip of a Slit In A Glass Block.

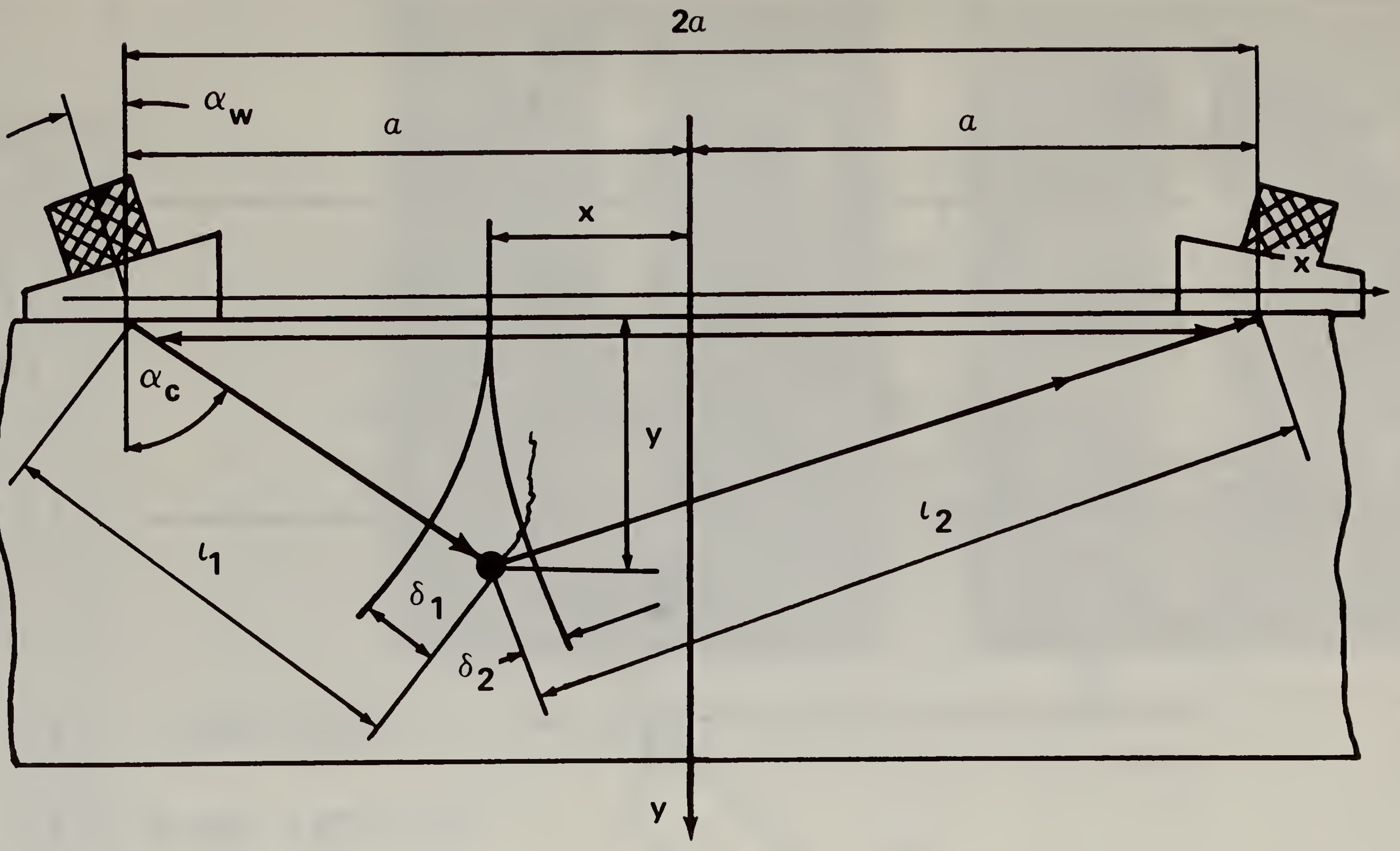


Figure 3. Triangle of Diffraction With A P Surface Wave As Reference.

$$Z = \frac{V\cos\beta}{2}\Delta T$$

Z - DEPTH OF CRACK

V - SOUND VELOCITY

ΔT - TIME DELAY

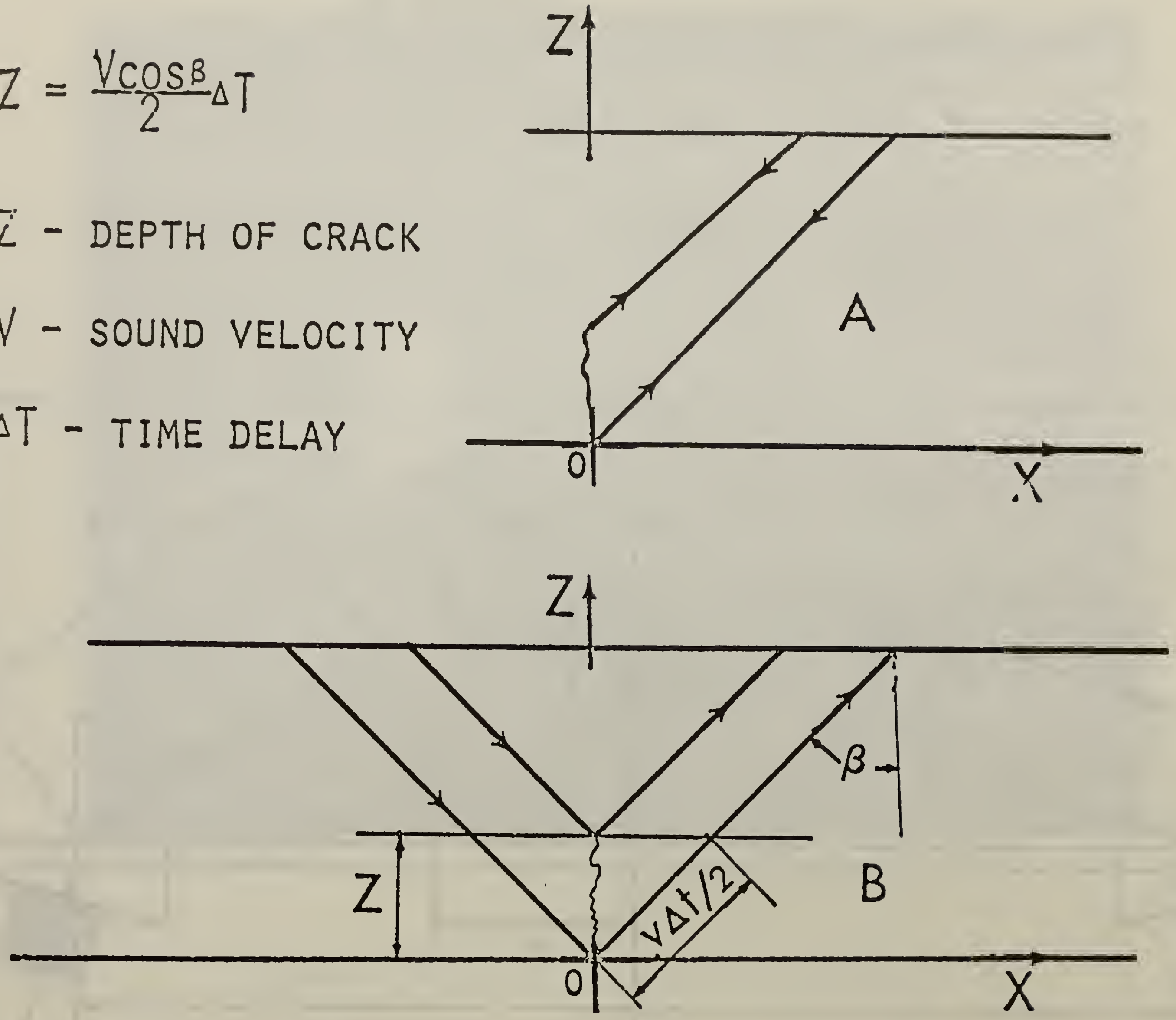


Figure 4. Sizing Of Cracks With Tip Diffracted Waves (A) Single Transducer Technique (B) Double Transducer Technique.

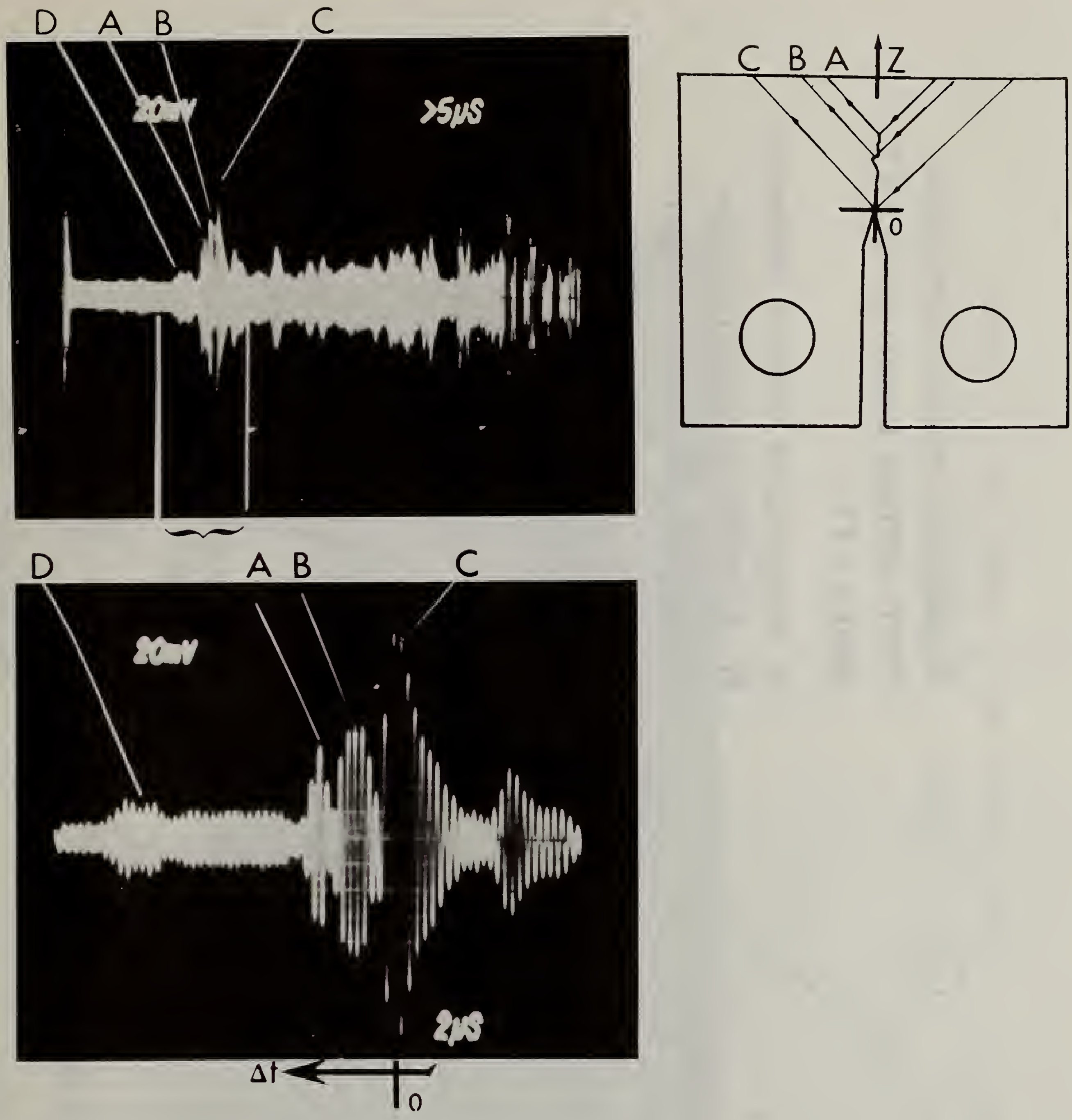


Figure 5. Noisy Background of the Oscilloscope Trace. The expanded Section Contains: (A) A Signal Diffracted From The Tip Of The Crack (B) Signals From Protrusions On The Crack Surface (C) A Signal Diffracted From The Tip Of The Notch and (D) Noise Signals From The Material. (C) Is The Zero-Reference Point. Time ΔT Is Measured From (C) To The Left.

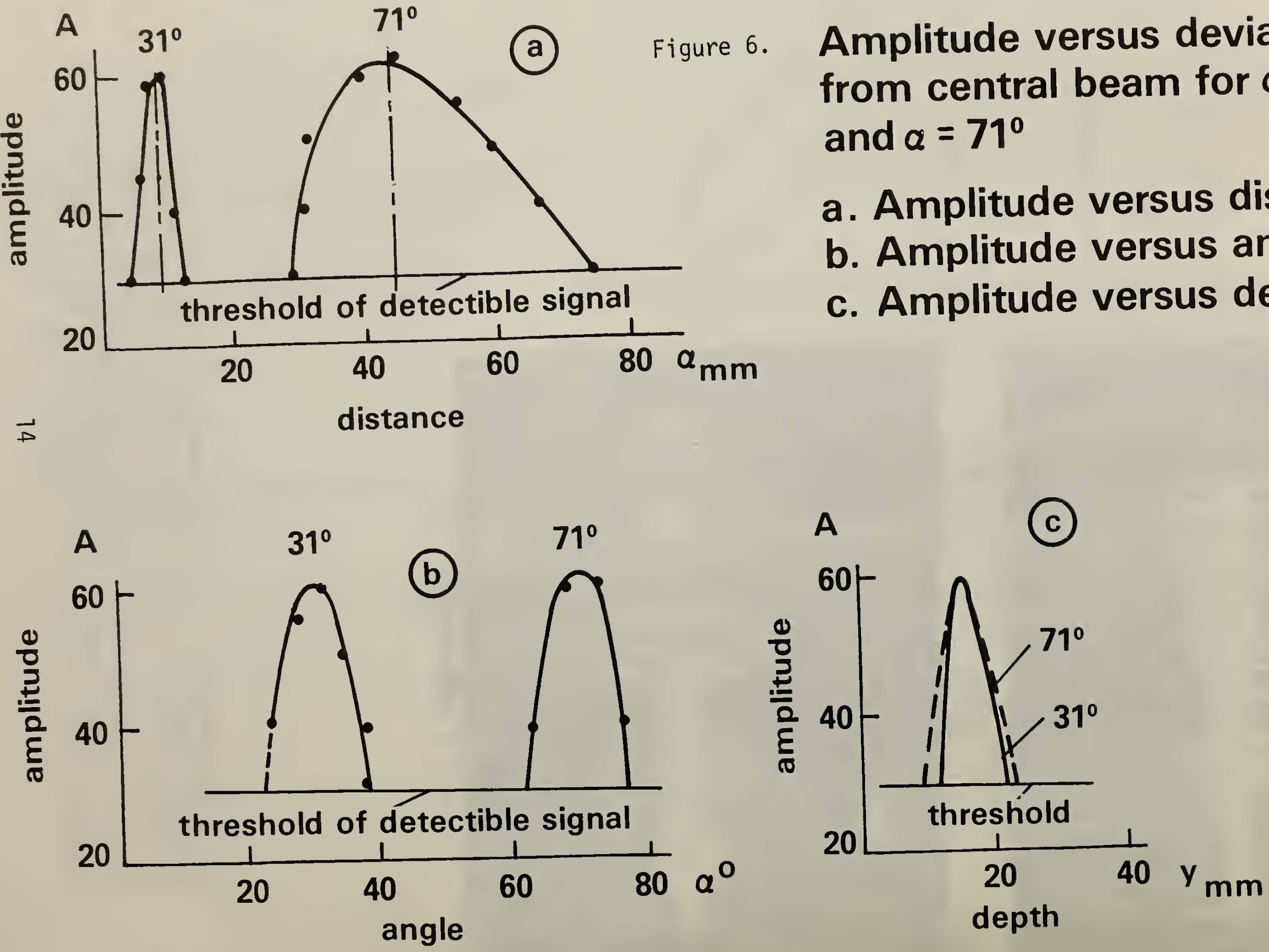


Figure 6. **Amplitude versus deviation from central beam for $\alpha = 31°$ and $\alpha = 71°$**

a. Amplitude versus distance
b. Amplitude versus angle
c. Amplitude versus depth

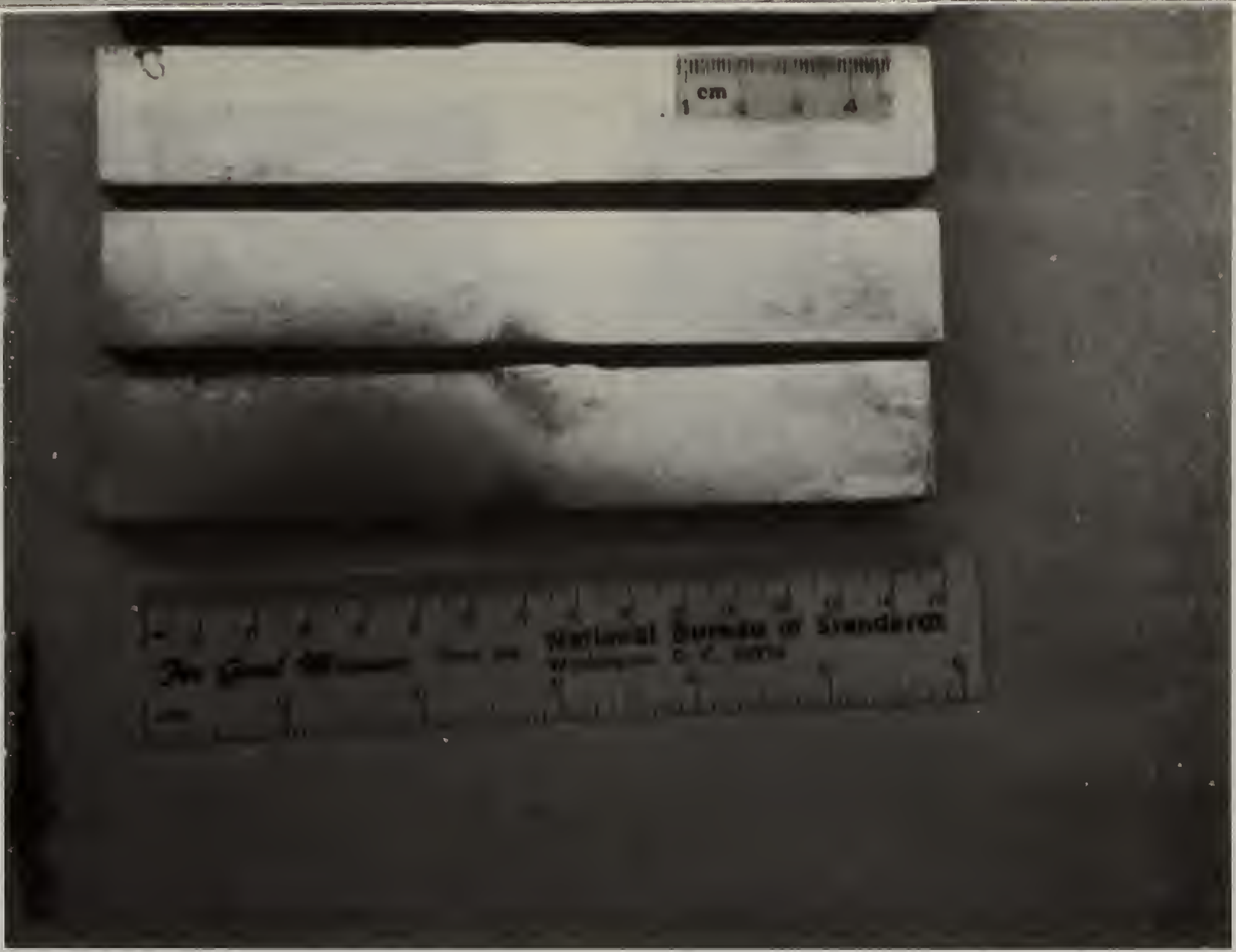


Figure 7. Specimens With Inwelded Cracks

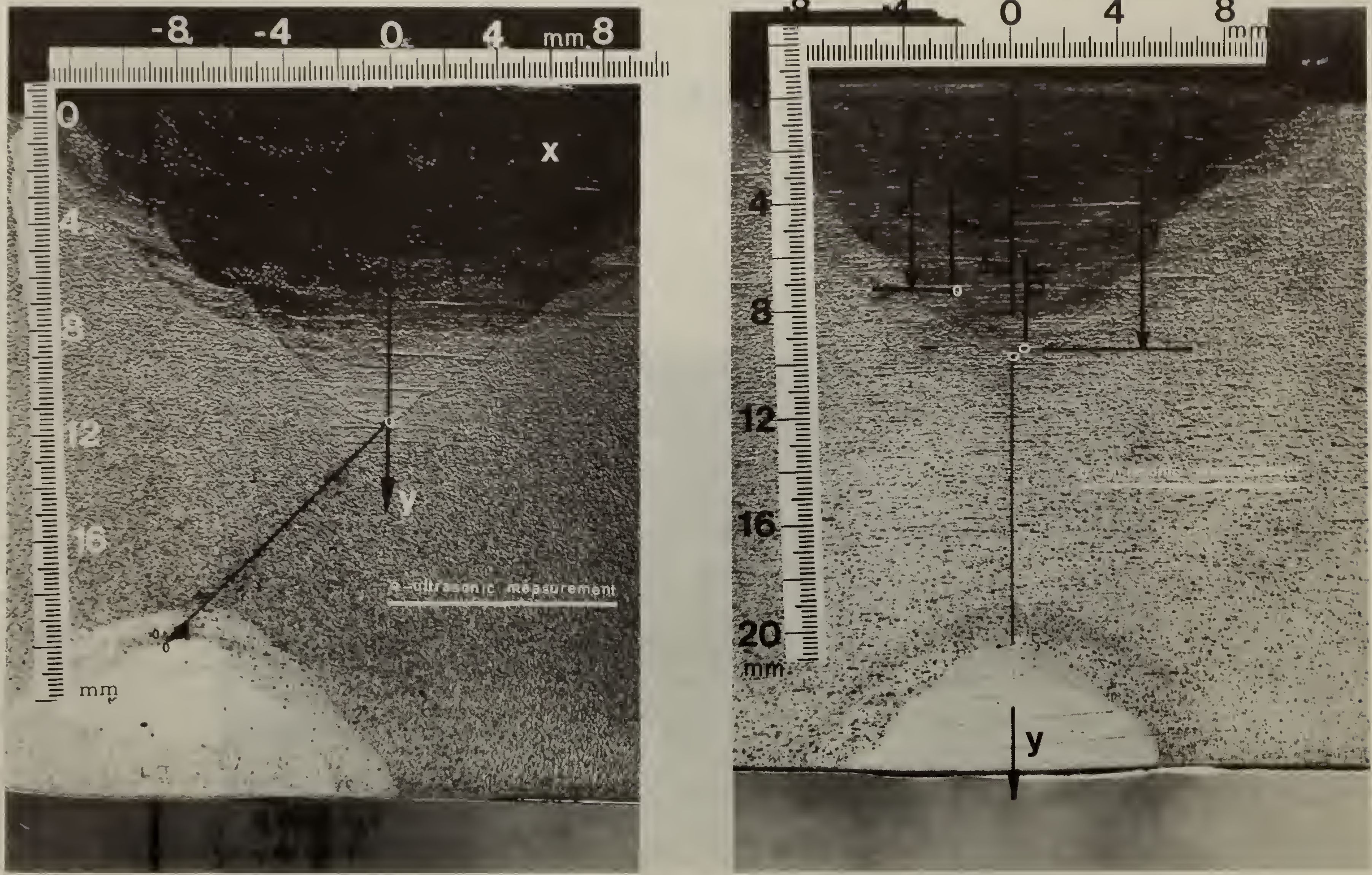


Figure 8. Cross Section of As Welded Specimens With Normal and 45° Inwelded Cracks

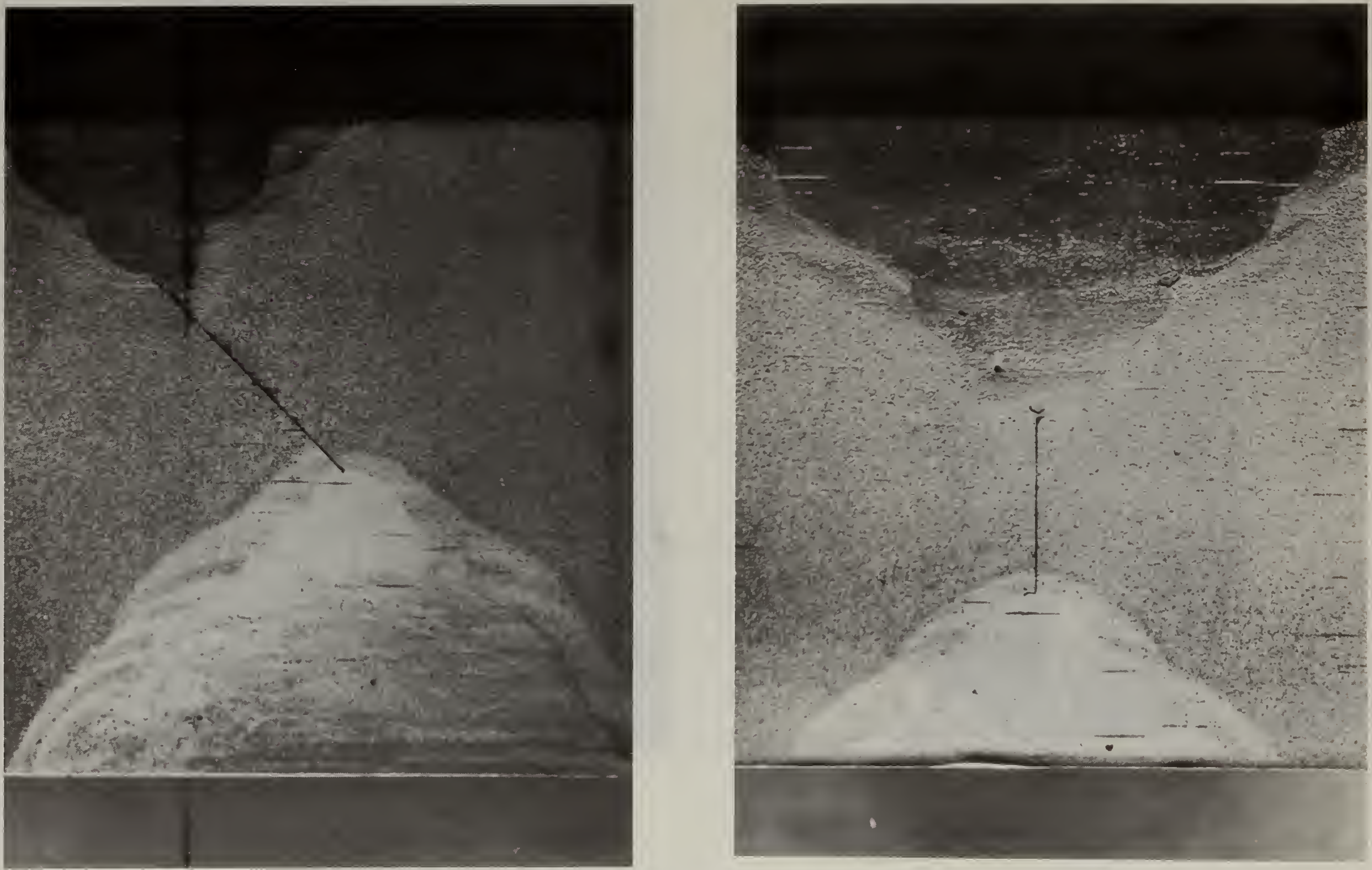


Figure 9. Cross Section of Machined Specimens With Normal and 45° Inwelded Cracks

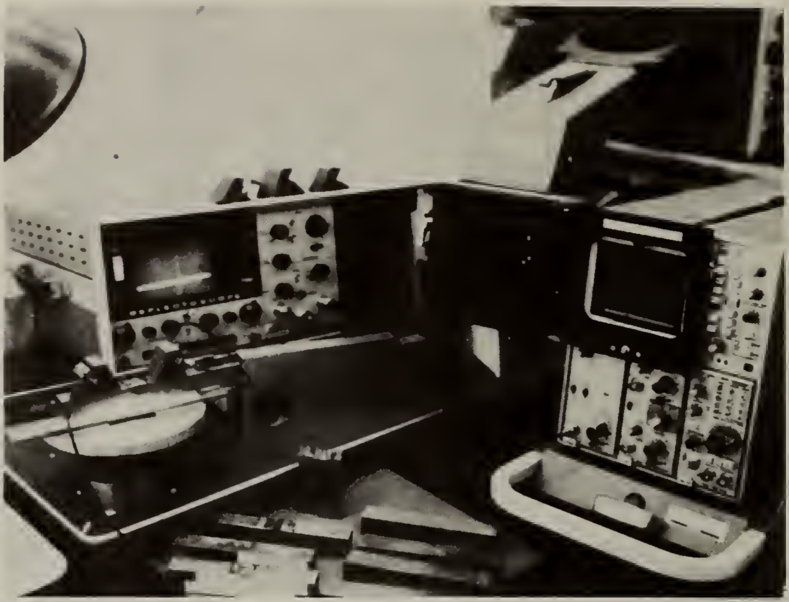


Figure 10. Experimental Set-Up

Figure 11. Transducer Arrangement

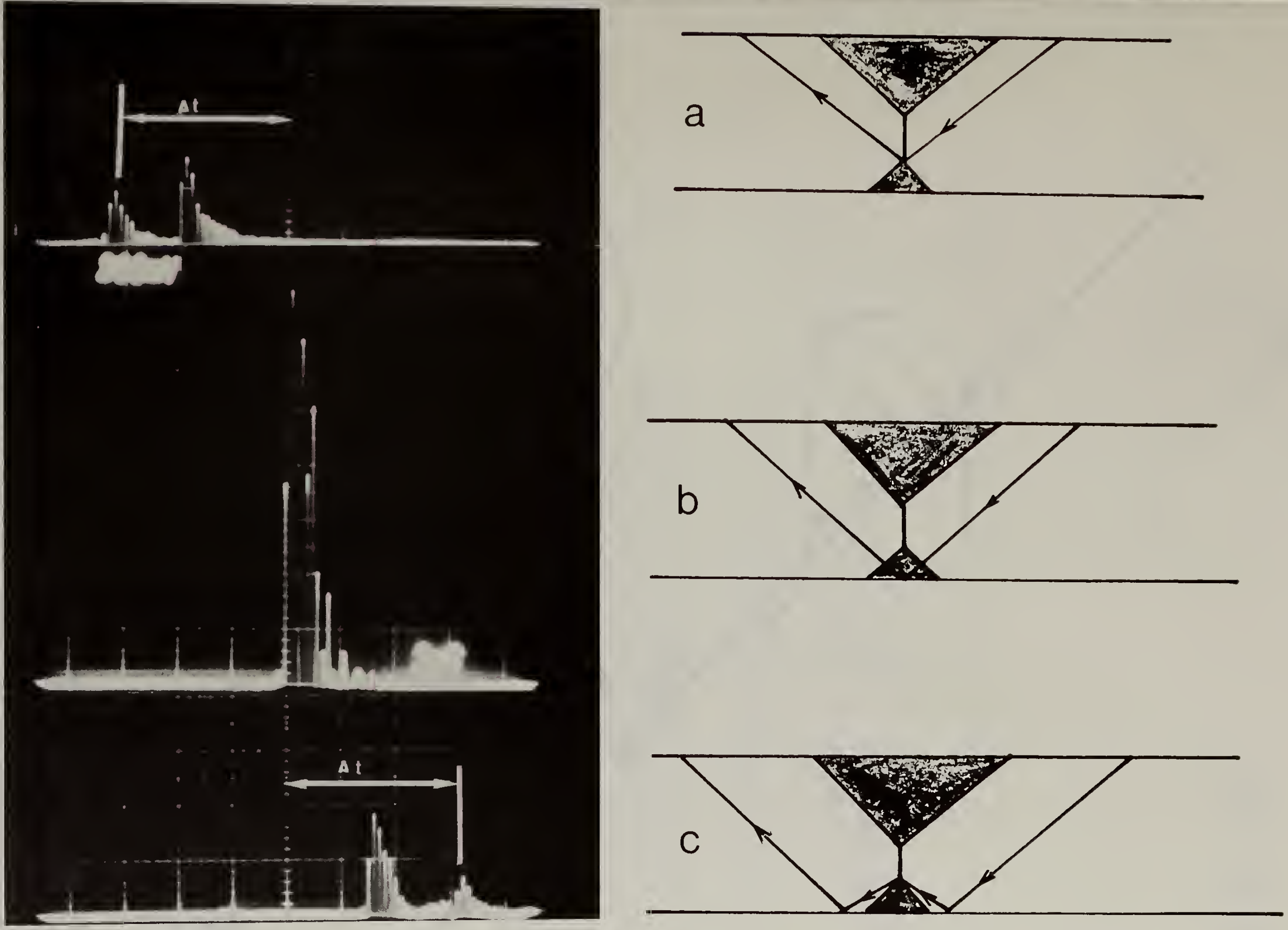


Figure 12. Oscilloscopic Trace of (a) Direct Beam, (b) Reference Signals, and (c) Double-skip Beam. The signal to the Left and to the right of the tip-diffracted signal is the back-wall reflection with transducers shifted from their maximum amplitude positions.

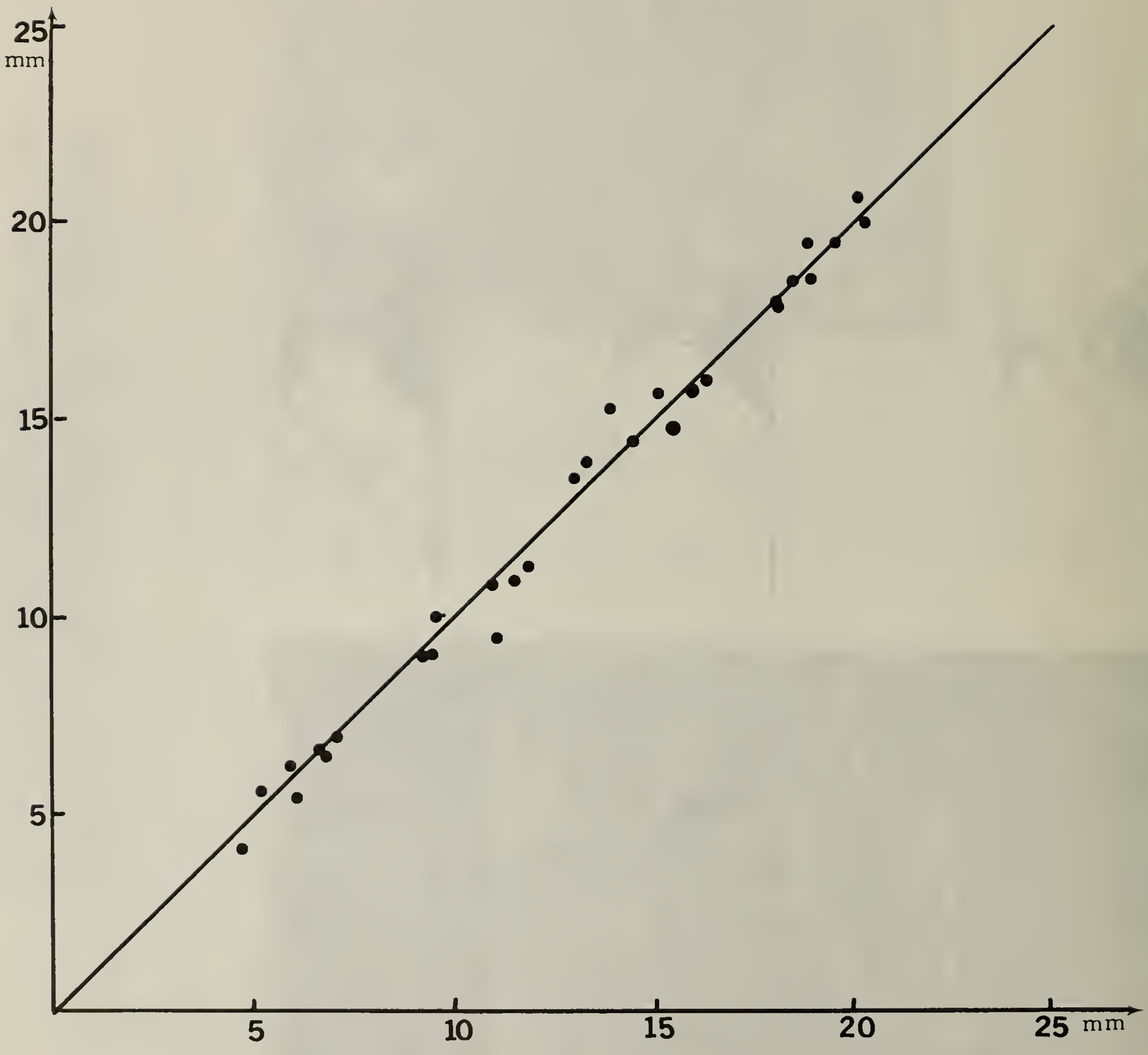
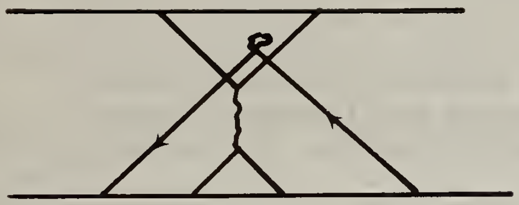
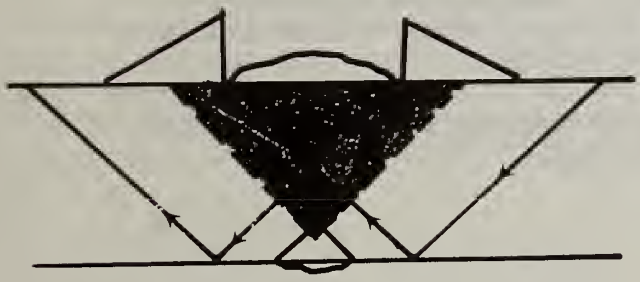


Figure 13. Ultrasonic depth measurements compared with direct depth measurements of "inwelded cracks". Direct measurements were taken at the outside surface and ultrasonic measurements in the middle of the specimen.



Noise from grains and small imperfections.

Multiple reflections from crack surface when one transducer is used.



Large dead zone because of weld crown when a direct beam is used.

Poor resolution. The strong backward signal mask the weak diffracted signal.

Figure 14. Schematic Presentation of Some Problems In Sizing Cracks in Welds.

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The possibility of applying an ultrasonic diffraction method for dimensioning of crack-like defects in welds was investigated. A feasibility study was carried out and optimum test conditions were established using a series of test specimens with narrow slits. A series of welded specimens with in-weld cracks were tested. The possibility of using a quantitative diffraction technique for nondestructive examination of pipeline welds in field conditions is discussed.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Compressional (P) modes; cracks; defect characterization; dimensioning; one-transducer technique; shear (S) mode; ultrasonic diffraction; and welds.

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