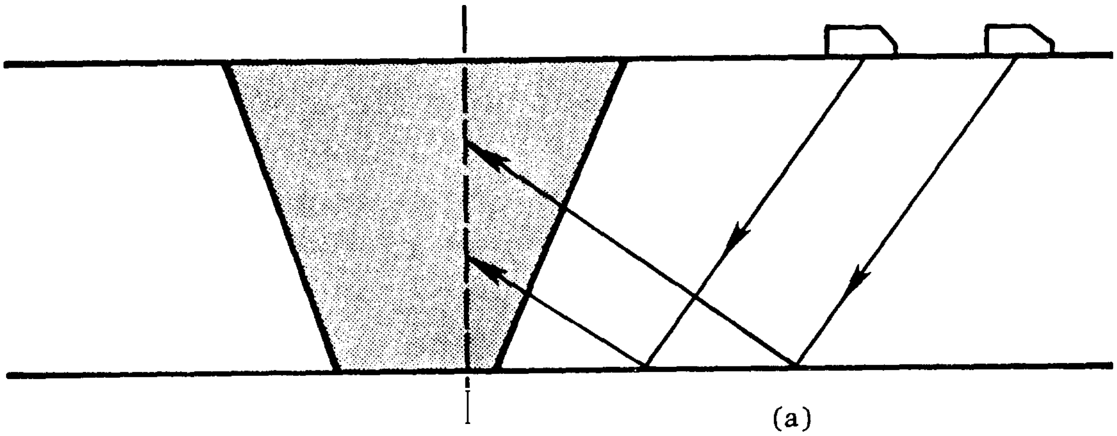
VI. STATE-OF-THE-ART OF ULTRASONIC METHODS FOR WELDS

The essentials of the conventional angle beam weld interrogation method are shown in Figure 42a. Appropriate transducer motion in a direction perpendicular to the center line of the weld will provide an interrogation of any vertical cross section of the weldment. The transducer is also indexed into the plane of the paper to provide a volumetric interrogation. Straight beam interrogation is performed in the heat-affected zone to be assured that laminar type flaws do not prevent the angle beam from entering the weldment. The straight beam is also used to interrogate the weldment whenever the weld crown is sufficiently smooth. However, the roughness and contour of the crown generally precludes such an interrogation by a straight beam. Figure 42b, shows a weld design that allows such an interrogation.

The orientation of the flaw with respect to the interrogating beam was responsible for the consideration of changes in the use of the single transducer. As we have seen a flaw oriented nearly normal to the inspection surface is totally dependent upon flaw surface roughness and contour for detection; there is essentially a zero probability of detection for such an ideally flat and smooth planar flaw. Since these flaws are typified by cracks and lack of fusion, the criticality involved necessitated a change in the weld interrogation procedure. The initial attempts were due to Lack [33] and consisted of using the pitch-catch arrangement shown in Figure 43. The procedure did present increased detection for nearly-normal cracks; however, there was a decided lack of quantitative ability. The procedure is best for flaws much larger than the beam at the detection plane. For the situation where a nearly vertical flaw breaks the surface, the procedure can be useful to estimate the depth of the interior tip of the flaw. The procedure :involve?; varying the beam angle until a specified amplitude difference is noted. By using geometric deductions, the depth of the crack may be obtained.[51,54]

Lack[33] arid Sproule [32] of England, were the first to propose the double transducer or tandem arrangement of Figure 15. This transducer arrangement continues to be used extensively in Europe, or for that matter, everywhere



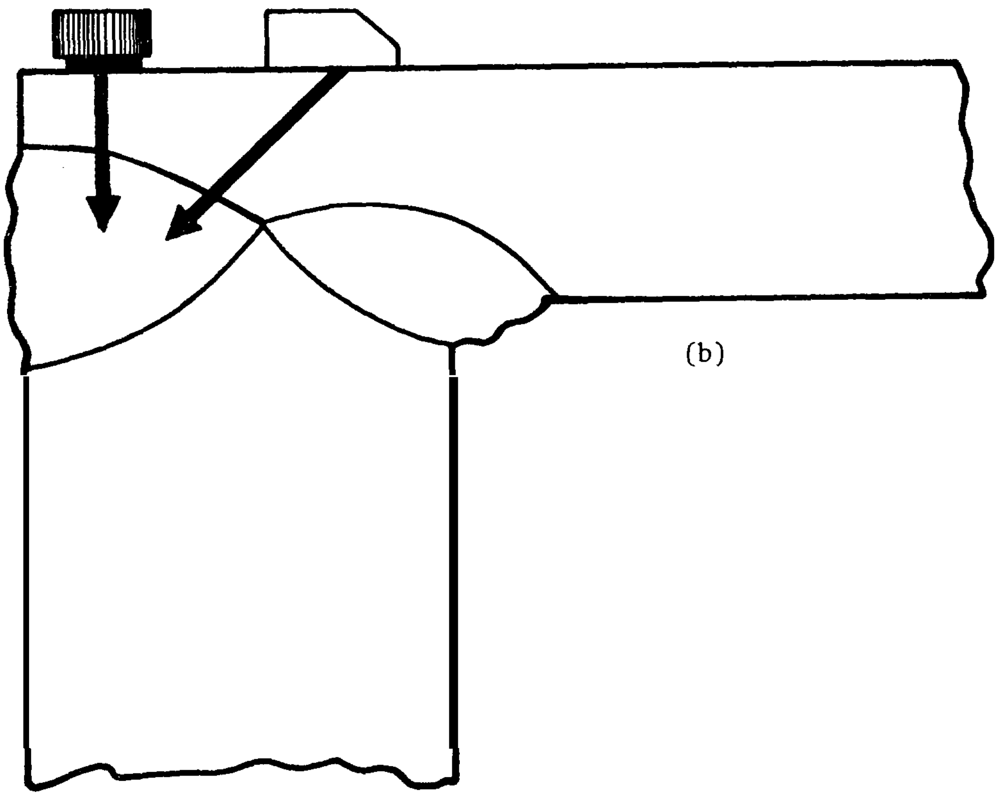


Figure *42* - Ultrasonic interrogation of weldments by both straight and angle beams.

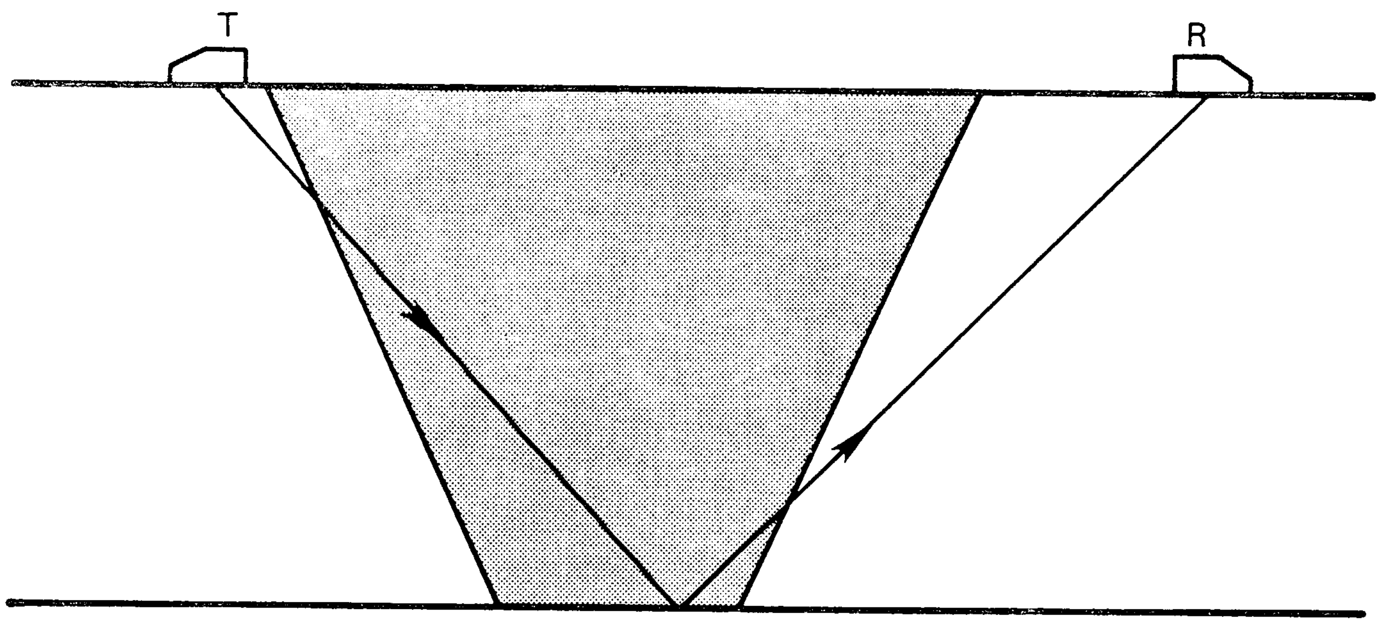
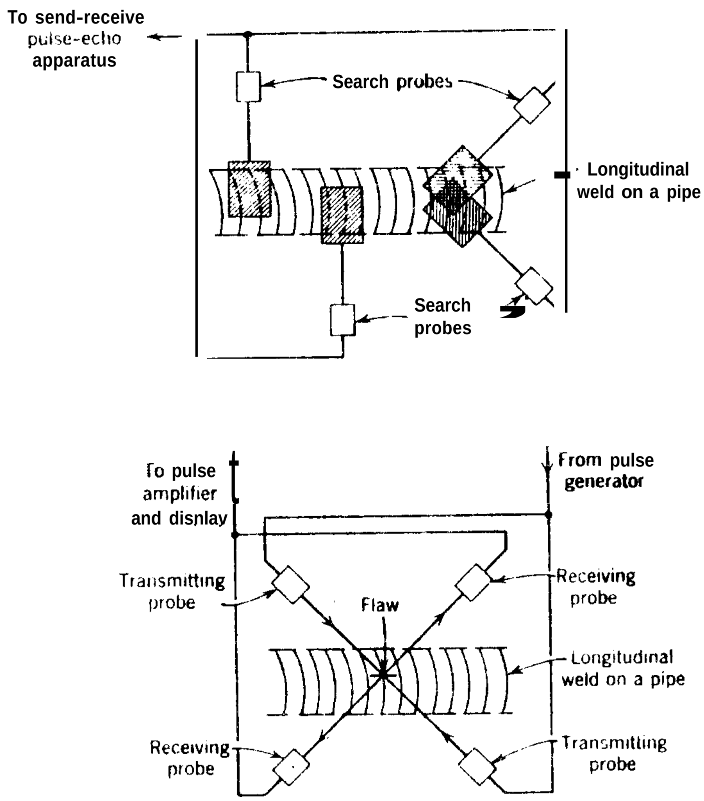


Figure *43* **– One of the initial double transducer arrangement for weld interrogation. After Lack (33).**

except in the United States. Other multiple transducer arrangements are shown in Figure 44. In each of these situations an attempt is being made to minimize the influence of flaw orientation.

An additional complication is presented when a cladded surface is used. Cladding is used extensively in the nuclear power generating industry to protect ferritic components in a high temperature environment. Hedden(55) has indicated that the reflection qualities are greatly affected by the cladded surface; see Figure 45. In this display, the amplitude of the reflected ultrasound from a 180mm thick plate is shown. The amplitude scan was produced by a pair of 2¼ MHz transducers operating in the pitch-catch mode. It appears that even grinding can, at best, reduce the initial 12 db noise level down to a 6 db level. Mayer (56) suggests that this effect can be minimized by the choice of the cladding process -i.e., band cladding has a lower scattering effect upon the incident ultrasound than manual cladding with electrodes.

Automatic ultrasonic scanning systems have been in use in some form essentially since the advent of the ultrasonic method. Such systems are of particular interest and need for the required periodic in-service inspections of nuclear power plants for a number of reasons. The obvious need is generated by the radiation levels involved. Also, the gargantuan amount of data that must be recorded and analyzed suggests the need for computerized storage facilities. Another reason is found in the need for reproducibility of data, e.g., the elimination of the human element. Also, from the standpoint of economics, the automated systems can reduce the inspection time. The function or the in-service inspections is primarily two fold - i.e., detection of flaws as well as a means of monitoring their growth. If one assumes that production and preservice inspections have eliminated all initial rejectable flaws, then the in-service inspections are concerned with the smaller or subcritical flaw content. It is the latter that constitutes the more exacting demands for the automated Ultrasonic systems. Any growth of flaws must be accurately detailed from the standpoint of changes in position coordinates to disclose changes in flaw size, position and orientation.



Two ways of connecting up an array of four angle probes are shown. *Top:* each probe sends and receives and scans the shaded area shown. All probes are connected to the same pulse generator and display unit. In this arrangement, the two probes at the left detect longitudinal cracks and the two at the right will detect transverse cracks. *Bottom:* two probes transmit pulses and two are receivers. Where no flaw is present, no echo is received in either receiver. If either a longitudinal or transverse crack is present, a signal appears in both pairs of probes. (Krautkramer Ultrasonics, Inc.)

Figure 44 - Multiple probe systems.

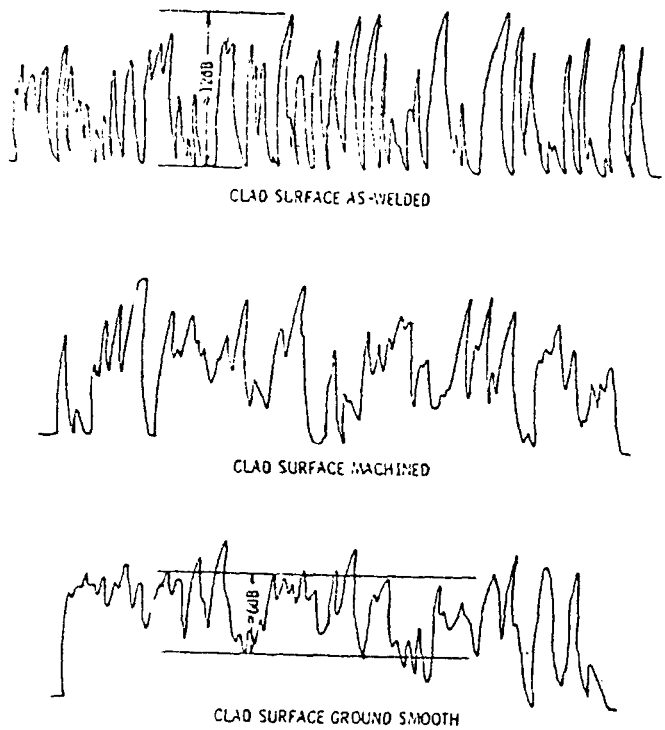


Figure *35* - Amplitude response scans from clad surfaces. Transducers were in a pitch - catch arrangement. After Hedden (55).

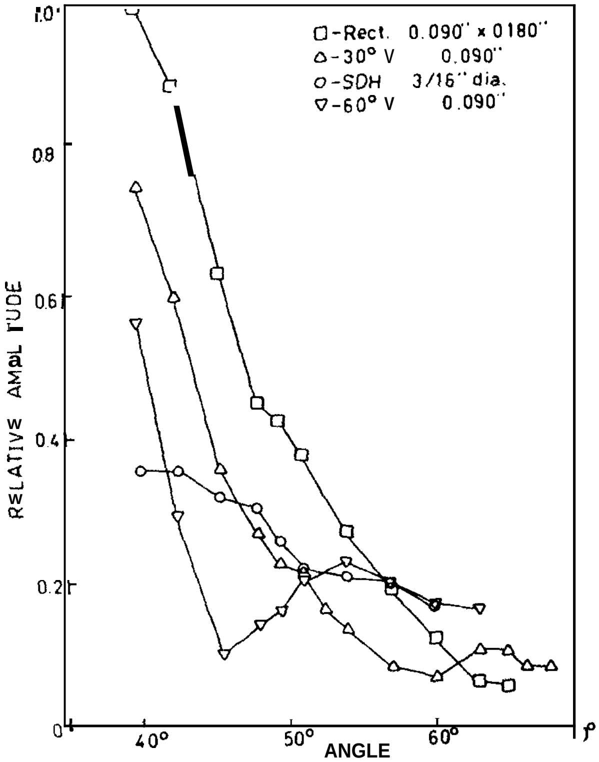
One of the common features of the automated systems is a means for rapid preprogrammed mechanical translation of the head containing the transducer(s). The means of performing the necessary translation are quite sophisticated and appear to be capable of performing their required function. Most systems scan at a prescribed rate until a recordable indication is noted; the scan is then either slowed down or the recording process is speeded up. The recording devices used have run the gamut from digital readouts, facsimily displays and regional or mapped displays. Moreover, many systems have provisions for the operator to override the automatic scanning to provide further exploratory data by using different beam entry angles and sensitivities in the vicinity of an indication. In this manner, more collaborative data is obtained for interpretation purposes. A number of the systems have television cameras to monitor the motion of the transducer head.

The literature indicates a general fascination with the mechanical, electronics and display components of the system. They are described in great detail; however, very little mention is made of the interpretation of the ultrasonic findings, nor is there any assessment of the abilities of the ultrasonic portion of the system. Do the systems perform their design mission? What are their strong points or their weak points? There is no verification of these notions. It is reasonable to assume that these questions have been **addressed** -- or have they? Perhaps the lack of information is a matter of company proprietary policy!

In the following, the status of the major problem areas of weld interrogation will be presented and analyzed.

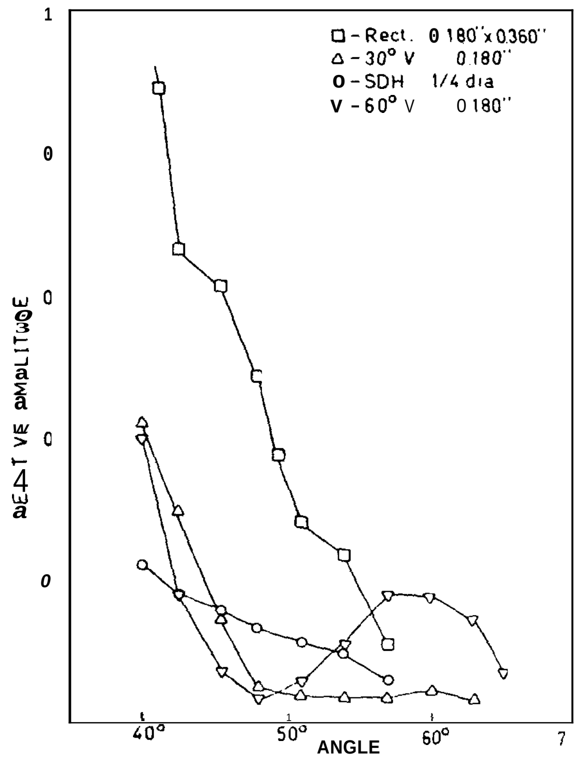
1. Interrogation Standards

There are a variety of reference reflectors that can be used to establish the interrogation sensitivity. The more common ones are rectangular and vee notches (30^o and 60^o), side drilled holes and flat bottom holes. It has been demonstrated that the reflections from notches are very sensitive to notch shape, ultrasonic frequency and the angle of incidence of the ultrasound.[57-59] Figure *46* presents some typical results and also indicates



three inch thick specimen

Figure 46 - Amplitude response from a variety of reference standards as a function of the incident angle at 2 1/4 MHz. After Ammirato (58).



six inch thick specimen

the influence of the thickness of the material being interrogated. Often material specifications do not rigidly indicate these parameters. Therefore, the rejection level can vary by an order of magnitude between **two** calibrations performed in accordance with the same specification. However, the main difficulty with the use of notches is that they cannot be reliably produced. For this reason, the side drilled hole has a decided advantage.[60] It is comparatively easy to produce and is insensitive to changes in the angle of incidence for the ultrasound. For those situations where a side drilled hole is not allowable, an external block containing the side drilled hole(s) is used.

To take into consideration flaw distance, an experimentally derived distance-amplitude-correction curve (DAC) is used. Figure 47 illustrates the generation of the DAC curve. The distance-amplitude response for any comhination of material and transducer is sought by noting the amplitude from side drilled holes located at a variety of path lengths. The resulting DAC curve is drawn on the operator's oscilloscope face to facilitate the disposition of any noted indications. For example, any indication whose amplitude is above the DAC curve may be cause for further investigation or outright rejection. The DAC curve is usually established using a block of material "acoustically similar" to the base material of the welded structure. However, no mention is made of how one establishes the acoustically similar condition. The decreasing DAC curve may also be compensated by electronic means such that the amplitude from the side drilled hole is constant over the total distance involved.[61] There are two main problems associated with the use of conventional DAC curve. First, the DAC curve is only valid for a uniform material and not for the bimetallic structure of a weld system. In the latter, the base material and weldment present two distinct attenuation coefficients. Second, the DAC curve is used to monitor the amplitude response from reflectors of any shape at any given distance. Since the distance dependency is a function of the shape of the reflector, the amplitude from reflectors of all shapes cannot be measured in terms of a particular reflector.

Figure 48 illustrates the situation where two identical flaws are located at the same path length from the transducer and according to the DAC curve should result in the same detected amplitude. However, the added higher weldment attenuation encountered in distance D during the detection of the number 2 flaw would result in much less observed amplitude. Therefore, the DAC curve is invalid when the attenuation of the weldment is significantly greater than the attenuation of the base material. Since the latter is definitely the rule, one can question the concept of the DAC standard. To appreciate the order of magnitude of the error, consider Figures 49 and 50. In Figure 49 the equi-amplitude lines of the ultrasound available for detection is shown for the case when the attenuations for the weldment and base material are equal. The attenuation is representative of mild steel. It should be noted that both identical flaws 1 and 2 would result in the same detected amplitude and that the same flaw located at position 3 would result in a greater detected amplitude. Both of the latter events can be expected since the detection process is distance dependent. However, as the attenuation of the weldment exceeds that of the base material the equi-amplitude lines become oriented parallel to the weldment/base material interface on the ultrasound source side; see Figure 50. The detected amplitude is no longer solely distance dependent. As indicated by horizontal amplitude sampling at the top of the weld, the amplitude difference can amount to a factor of 3 when the attenuation difference is approximately 40:1. The latter was the case for an inconel/steel weldment of a naval nuclear reactor.[62]

These notions were examined experimentally by the use of the block shown in Figure 51 of the inconel/steel weld system of Reference 62. The amplitude of ultrasound from surfaces just prior and after the weldment/base material as well as from a surface well within the weldment were examined; each time the ultrasound impinged upon the surfaces at normal incidence. The results are shown in Figure 52. As indicated, the influence of attenuation can be significant. Moreover, it was found that it was possible to predict the decrease in amplitude from the exponential decay formulization of attenuation.

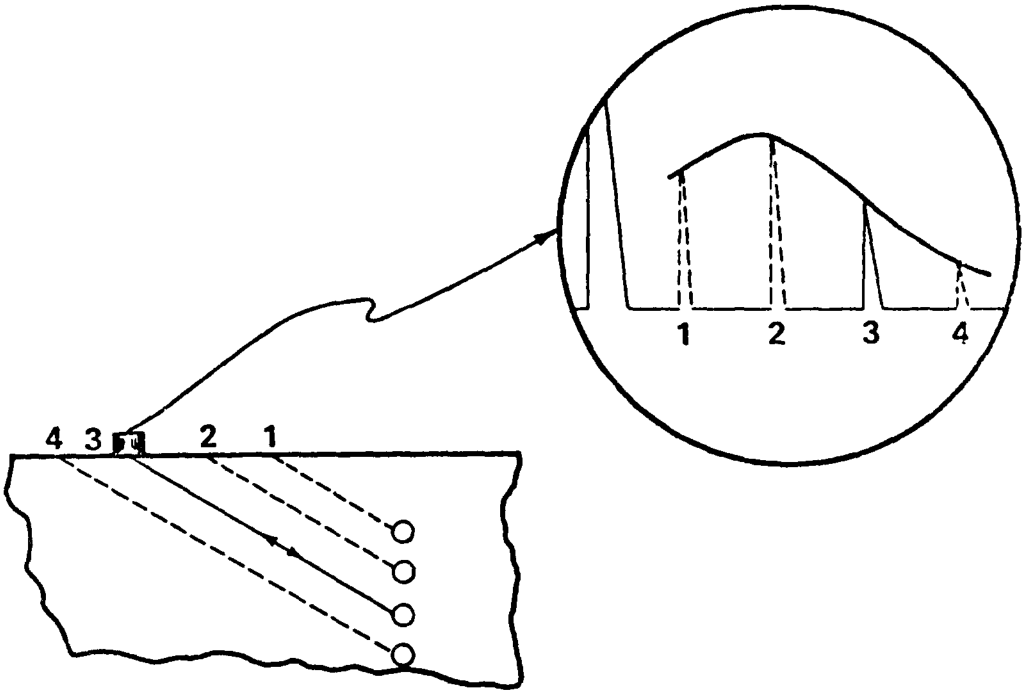


Figure 47 - Typical procedure for generating the distance-amplitude-correction curve (DAC). After Serabian (62).

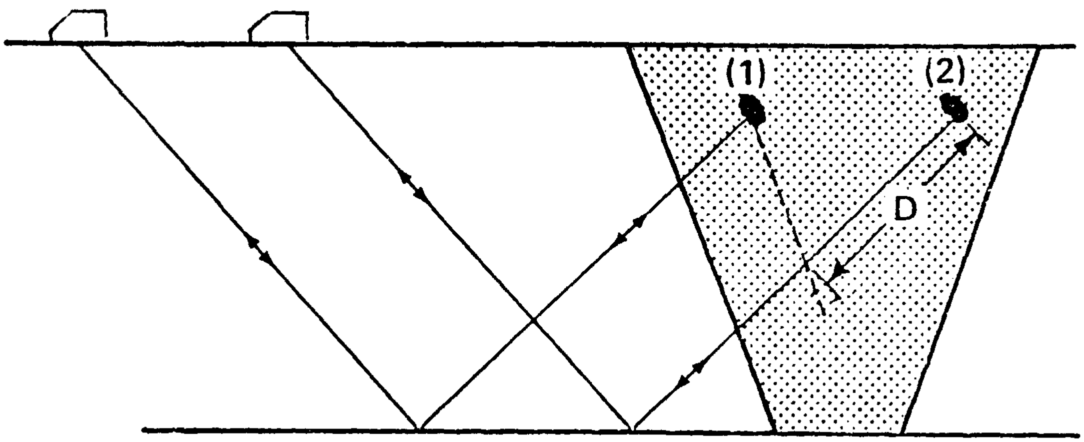


Figure 48 - Influence of the higher weldment attenuation. The flaw at position 2 would be noted as a smaller amplitude because of its greater distance (D) in the weldment. After Serabian (62).

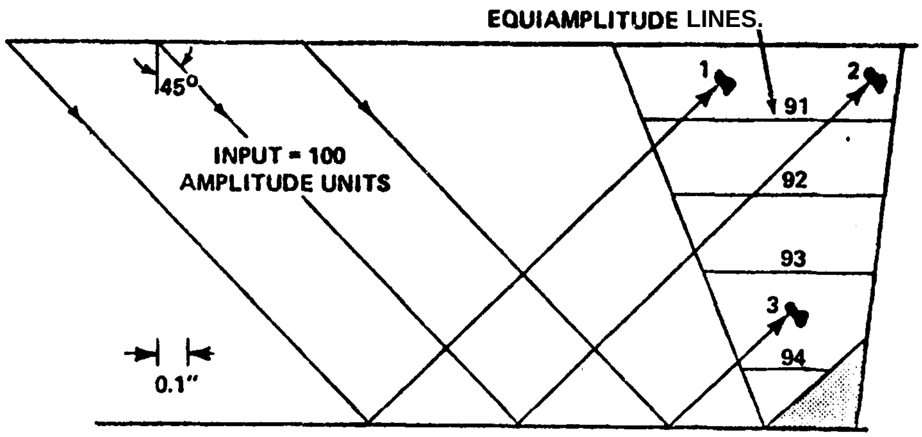


Figure 49 - Ultrasonic amplitude field available in the weldment for flaw detection when the attenuations in the base and weldment materials are equal. After Serabian (62).

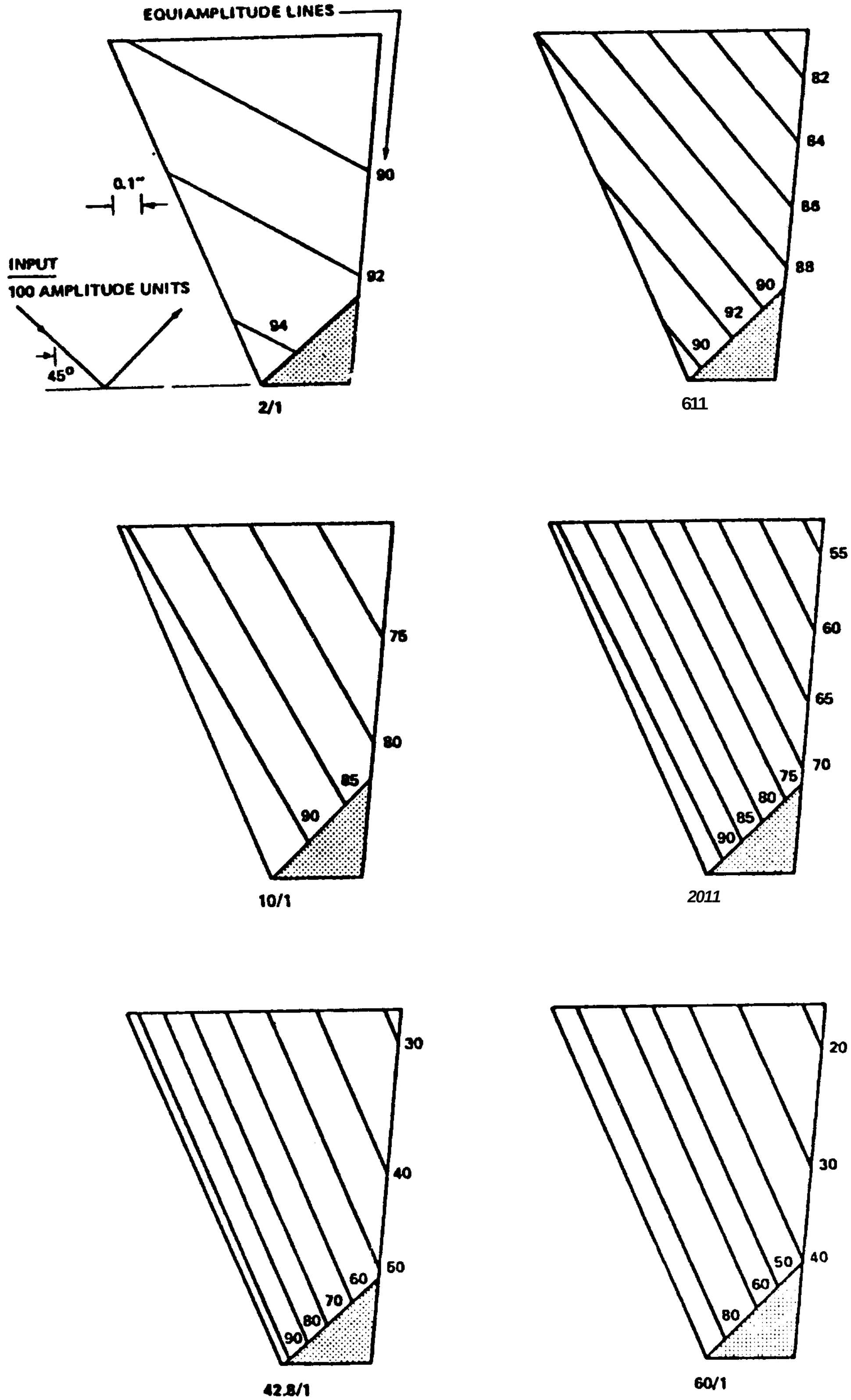


Figure 50 - Ultrasonic amplitude fields available in the weldment for flaw detection as a function of the ratio of weldment to base material attenuations. The weld system is steel/inconel and the interrogation is from the steel side. After Serabian (62).

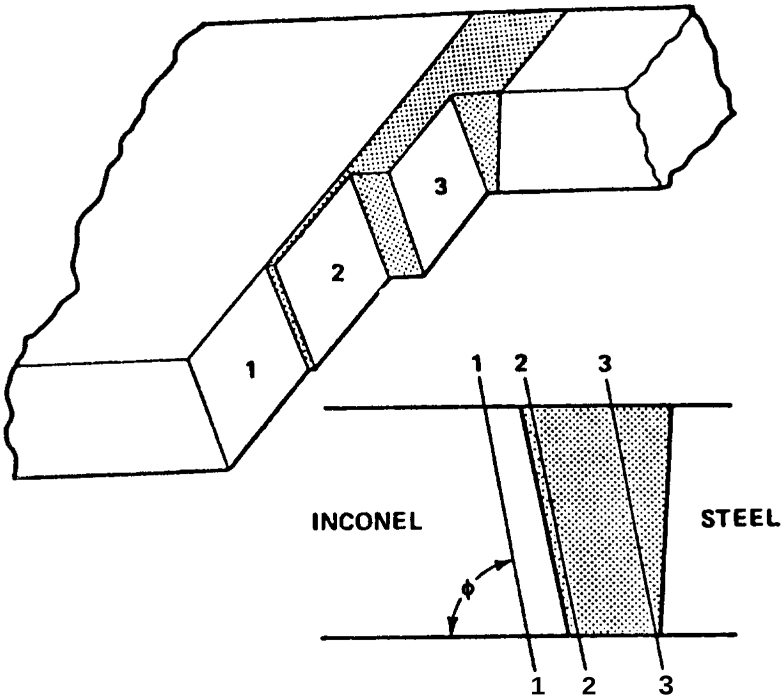


Figure 51 - Specimen used to examine the amplitude of ultrasound at selected planes within the weld system. After Serabian (62).

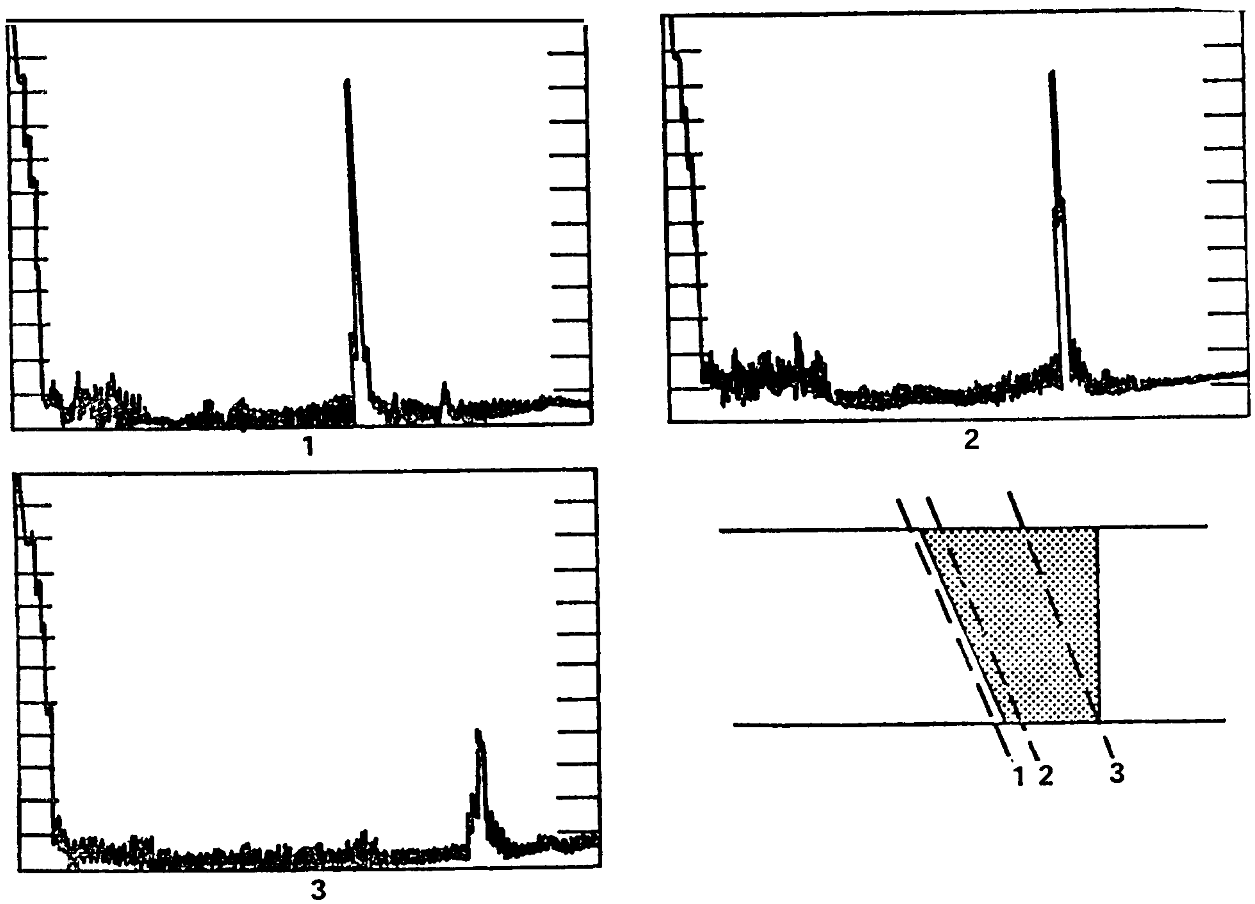


Figure 52 - The amplitudes of ultrasound noted at the cut surfaces of the specimen of Figure 51. After Serabian (62).

The initial corrective measures to eliminate the deficiency of the DAC curve produced by attenuation effects consisted of correcting the DAC curve to conform to the weldment attenuation. The ASME Boiler & Pressure Vessel Code was one of the first to adopt this concept; however, it was eliminated because no feasible method was found to make the amplitude transfer of the DAC from the base material to the weldment attenuation. The attempts to derive the so-called "transfer mechanism" did not consider the more basic concepts of attenuation. Such activities were relegated to crude quantitative reasoning, thus it is not surprising that it was dropped from the code requirements. One can question the basic reasoning of using an attenuation transfer mechanism to correct the DAC curve. This notion can be illustrated with Figure 53. When the attenuation of the weldment and base material are equal, the amplitude detected at the interrogating transducer from a flaw located at point P may be formulated as

$$A_p = A_o e^{-2\alpha_b (l_b + l_w)} \tag{8}$$

where A_o is indicative,of any losses at the weldment/base material interfaces and such flaw characteristics as size, orientation, contour and surface roughness; l_B and l_W are the path lengths traversed by the ultrasound in the base material and weldment, respectively. For the actual situation when the attenuation of the weldments greatly exceeds the base material attenuation, the detected amplitude is reduced and is given by:

$$A'_p = A_o e^{-(2\alpha_w l_W + 2\alpha_b l_b)} \tag{9}$$

where α_w and α_b are the attenuations in the weldment and base material, respectively. The reduction in amplitude in terms of the base material DAC is

$$\frac{A'_p}{A_p} = e^{-2(\alpha_w - \alpha_b)l_w} \qquad (10)$$

In order to use the base material DAC curve it is necessary to multiply the noted amplitude by a correction factor (C_α) given by:

$$C_\alpha = e^{2(\alpha_w - \alpha_b)l_w} \qquad (11)$$

It is apparent that the correction is due to the difference in the attenuations involved as well as path length the ultrasound traveled in the weldment. Therefore, going to a DAC curve based on the weldment attenuation does not relieve this dilemma. In essence, one must provide a point by point correction within the weldment to the base material DAC curve. This suggests the use of an on-line computer to provide the necessary correction. Such computers are available, relatively inexpensive and worthy of consideration. This would assume that the weldment attenuation can be measured. Techniques for measuring attenuation are well documented and can be incorporated into existing weld interrogation procedures with a modest developmental effort.[63,64,65]

Consider now the problem of evaluating a reflector of a different shape from the cylindrical reflector used to generate a working DAC curve for a particular interrogation situation. TABLE III indicates the theoretical reflected amplitude for a number of reflectors by a transducer with an area (a_r) while operating at a given wavelength (λ) and distance (s).[66] The reflectors chosen typify most of the natural flaws encountered. The third column of TABLE III lists the amplitudes from these reflectors in terms of the reflected amplitude from a cylindrical hole. It is significant to note that such amplitude ratios are all sensitive to distance and for the planar

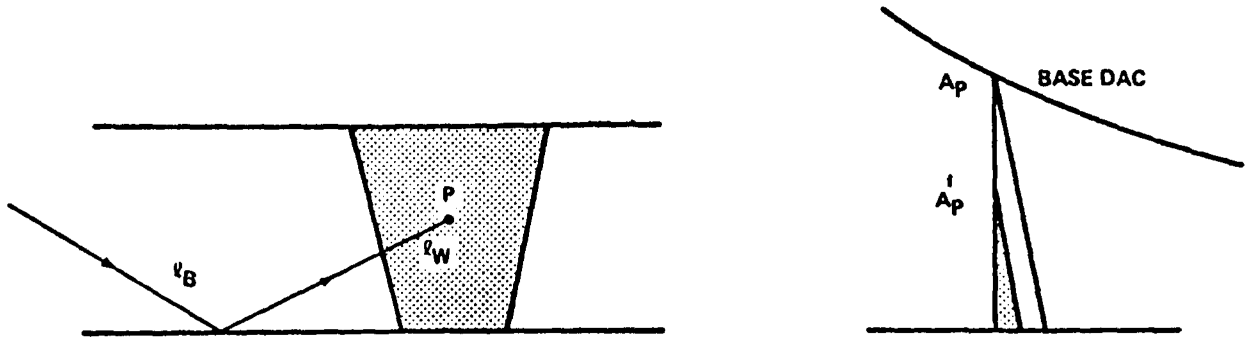


Figure 53 - Amplitude considerations for the generation of the weldment. attenuation correction factor (c_α). After Serabian (62).

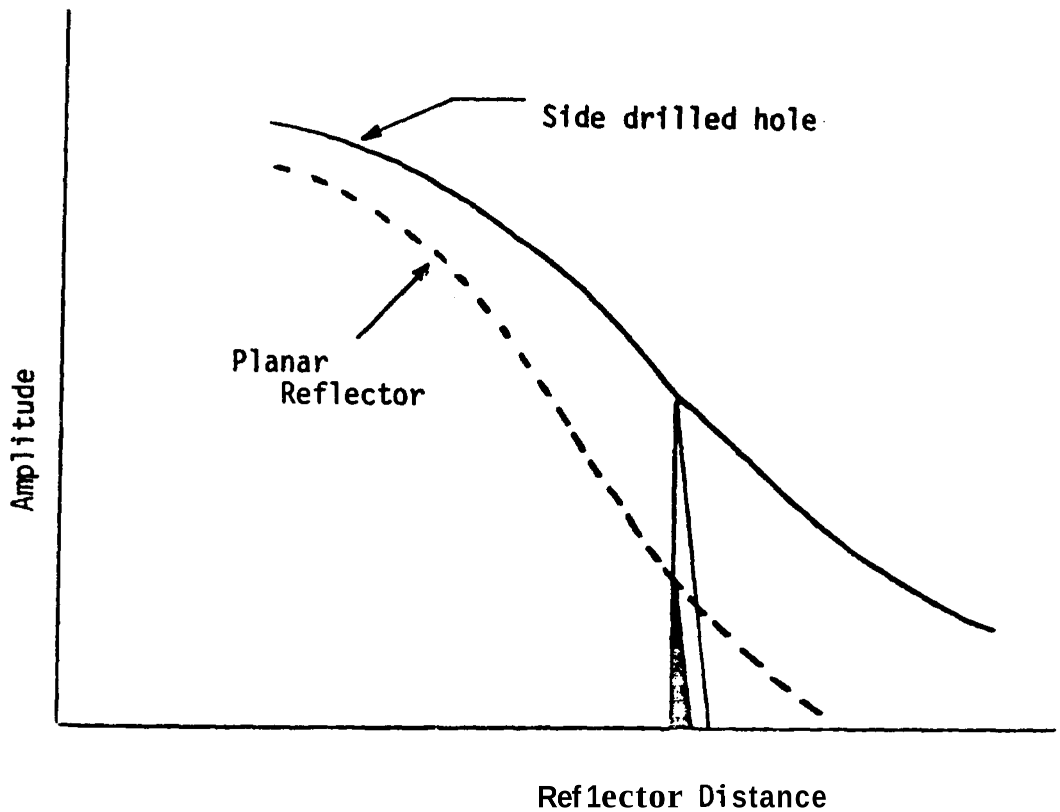


Figure 54 - The DAC curve as generated by side drilled holes underestimates the size of planar reflectors at large distances. After Serabian (62).

TABLE III

AMPLITUDE CONSIDERATIONS FOR VARIOUS REFLECTORS

TYPE OF REFLECTOR	REFLECTED AMPLITUDE	$\frac{A(\text{REFLECTOR})}{A(\text{SDH})}$
CYLINDER	$\frac{a_r}{\lambda}\sqrt{\frac{d_c}{S^3}}\, e^{-2\alpha S}$	$\sqrt{\frac{d'_c}{d_c}}$
PLANAR	$\frac{a_r d_p^2}{\lambda^2 S^2}\, e^{-2\alpha S}$	$\frac{d_p^2}{\lambda\sqrt{d_c}}\, S^{-1/2}$
SPHERE	$\frac{a_r d_s}{\lambda S^2}\, e^{-2\alpha S}$	$\sqrt{\frac{d_s}{d_c}}\, S^{-1/2}$
STRIP OF WIDTH ℓ_s	$\frac{a_r \ell_s}{\lambda^3 S^3}\, e^{-2\alpha S}$	$\frac{\ell_s}{\lambda^2\sqrt{d_s}}\, S^{-3/2}$

a_r - receiver area

d_c - cylinder diameter

d_p - disc diameter

d_s - sphere diameter

S - flaw distance in far field

λ - wave length

A - amplitude response

and strip reflectors there is also a wavelength sensitivity present. Therefore, one cannot quantitatively monitor the amplitude from any reflector with a DAC curve generated by a reference cylindrical reflector. The impact of this is illustrated in Figure 54. It can be seen that the distance dependency can produce a much smaller detected amplitude from a planar reflector. 'Therefore, a critical size flaw would be underestimated when it is located at a large distance.

2. Influence of Weld Geometry

A major problem involved in weld interrogation is the geometry of a welded joint. As indicated in Figure 55, the crown can limit the transducer motion. If the attenuation of the weld is excessive, a complete V pulse cannot be considered, thus, the extent of the weldment that can be interrogated is limited. The latter is the case for some stainless steel weldments.

Another weld geometry aspect is the practice of counterboring on the inside diameter of pipe welds to improve the weld joint fitup. Figure 56 [(67)] depicts this situation for a typical taper of 14°. The resulting taper produces a longitudinal wave by mode conversion. The interaction of the longitudinal wave with the relatively rough crown surface can produce extraneous reflections. Since the velocity of the longitudinal wave is approximately twice that of the shear wave one cannot differentiate the real shear wave indications from such extraneous reflections. The end effect is that the interrogation can produce misleading spurious indications. The problem can be further compounded by a lack of information about the location of the taper and the taper angle. The obvious solution to the counterbore problem is to increase the length of the counterbore such that the interrogating shear wave travels through a uniform material thickness.

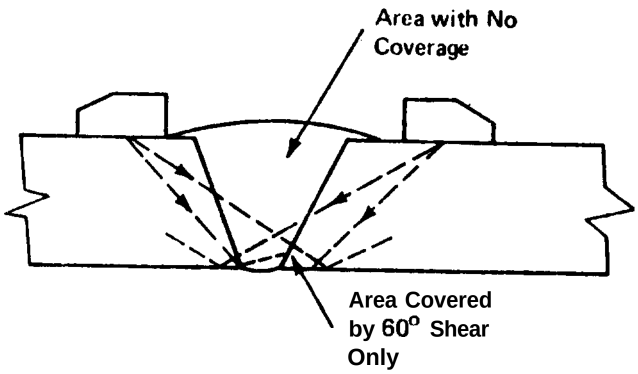


Figure **55 - The need for V-path scanning due to a limited coverage caused by a large weld crown. From reference 67.**

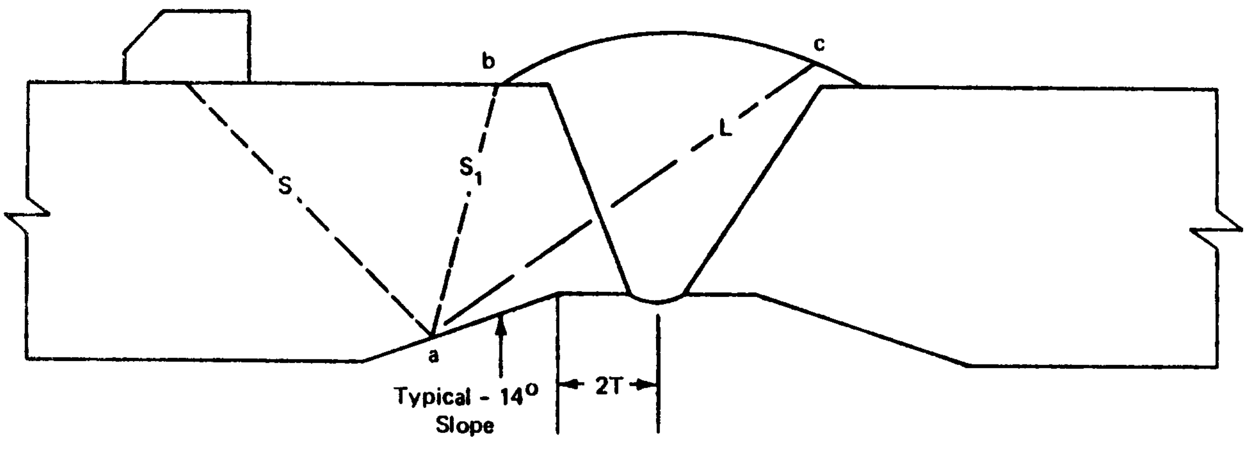


Figure 56 - **A schematic representation showing how an ultrasonic shear wave (S) can interact with the counterbore chamfer to produce shear wave (S) and longitudinal (L) wave components. From reference 67.**

3. Acoustic Anisotropy in Weldments

Weldments as typified by some inconels and stainless steels have a course grain dendritic structure. These grains tend to grow preferentially in the weld-pass and weld-metal build up directions. Depending upon the weld thickness, dendrites up to 10mm in length and lmm across have been observed. Such microstructure results in acoustical anisotropy, unusually high attenuation, low ultrasonic signal to noise ratio, and the generation of spurious indications which cannot be identified as emmanating from actual flaws or specimen geometry. [18,19,68] G. Herberg, et al, [69] have indicated that the heat-affected zone of austenitic steel welds can also be highly anisotropic and noisy. This further compounds the interrogation problem. The interrogation of such materials has been beseiged by many difficulties which are perhaps best summarized by one individual. He describes the perplexing problem for stainless steel in the following manner, "sometimes we can inspect stainless steel welds very easily, sometimes we cannot inspect stainless steel at all, and sometimes we cannot ascertain that we have (indeed) inspected stainless steel welds". [67] This problem has attracted the attention of many investigators, which is a measure of its importance and urgency.

The acoustic anisotropy can be described in terms of velocity and attenuation. Keupperman and Reimann [18] describe such a study in 308 stainless steel. They used the specimen indicated in Figure 57; x-ray diffraction disclosed preferred orientation, predominately in the Y and Z directions. As displayed in Figure 58, the longitudinal wave velocities in the three indicated directions showed very little differences. However, there were appreciable shear wave velocity differences and a strong dependence on the polarization angle; see Figure 59. The fact that both fast and slow shear waves exists is indicative of a preferred texture or orientation. It is significant to note that the average velocity is essentially constant and approaches the shear wave velocity of a randomly oriented grain structure.

The usual entry angle for angle beam interrogation is either 45 or 60° from the principal axes of the weldment shown in Figure 57. Therefore, the prop-

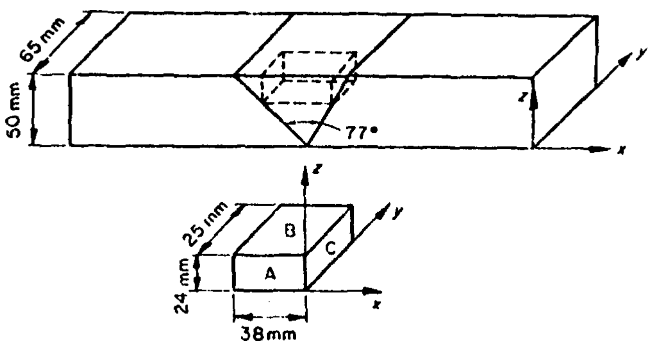


Figure 57 - Weld-metal coupon used by Kupperman and Reimann (18) to obtain acoustic properties of 308 ss.

Propagation direction	Sound velocity [10^6 mm s^{-1} (± 0.02)]	Relative signal strength'
x	5.69	M
Y	5.63	M
z	5.43	S

S — strong; M — moderate.

Figure 58 - Velocity of longitudinal waves in 308 ss weldment. After Kupperman and Reimann (18).

Propagation directions	Polarization directions	Velocity [10^6 mm s^{-1} (± 0.02)]	Relative signal strength'	Average velocity [10^6 mm s^{-1}]	Difference in velocity [10^6 mm s^{-1}]
x	y	2.97	M	3.34	0.73
x	z	3.70	W		
y	x	2.92	M	3.39	0.93
y	z	3.85	S		
z	x	(2.85) (3.9)[b]	W	3.34	0.98
z	y	3.83	M		

a, S — strong; M — moderate; W — weak.

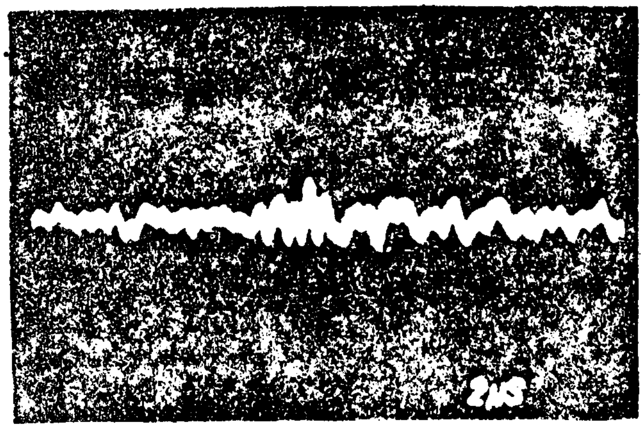
b, A weak signal from both shear waves was evident.

Figure 59 - Velocity of shear weves in 308 ss weldment. After Kupperman and Reimann (18).

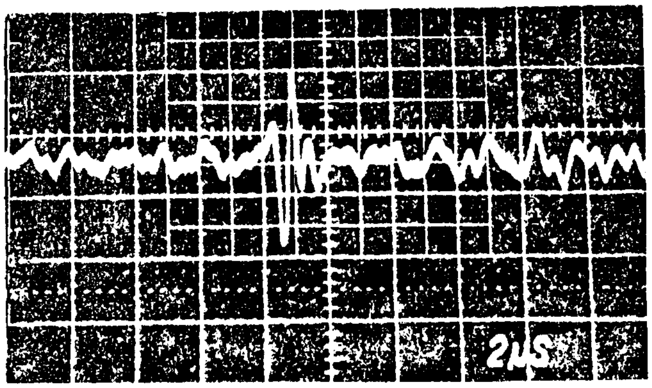
agation of shear waves will encounter impedance differences primarily due to velocity changes. The end result of this is an appreciable amount of mode conversion since the ultrasound will approach the dendritic structure with a polarization that is not parallel to either of the two preferred orientations. Because the surface at each crystallite is significantly large, the reflected components of the mode conversion can have relatively high amplitudes. These reflected components are responsible for the high noise levels observed during the interrogation of such materials. For the case whe - the polarization of the shear wave is in the horizontal or XY plane, there is no mode conversion, which should result in less attenuation and noise. This notion is shown in Figure 60, [18] for a 45° shear wave angle beam incident normal to the axis of a cylindrical reflector along the Y axis, The longitudinal wave results for the same entry angle is also shown. It is evident that the selection of proper polarization angle can substantially enhance the detecting ability of a shear wave interrogation. The influence of shear wave polarization in Figure 61, illustrates much the same results for a highly attenuating inconel pipe weld. [62] As in the previous stainless steel work, there was no preferred orientation in the longitudinal direction. It was found that the difference in the attenuation because of polarization in the highly attenuating inconel material did not persist above approximately 3 MHz.

The enhancement of detecting ability by the reduction of attenuation [62,70,71] and noise [72,73] has been studied by a number of investigators. Both attenuation and noise are governed by grain size, the presence of a preferred texture, frequency, and the mode of ultrasound. Greater utilization is being made of the longitudinal mode for interrogation purposes. [69,74] Attentuation may also be caused by thedegree of the transducer damping and the type of data presentation used; see Figure 62. [75]

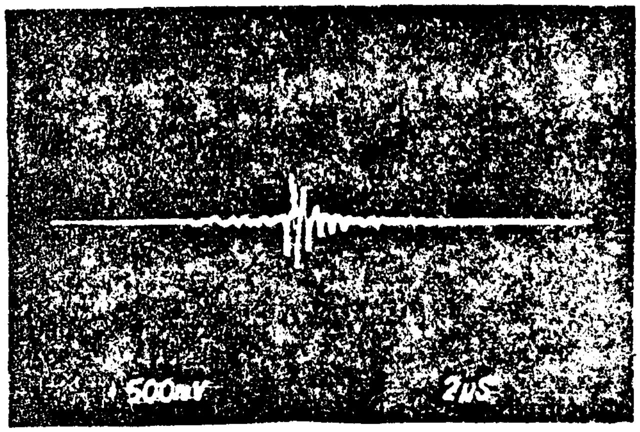
Ermolov and Pilin [72] have indicated a number of techniques that can be used for noise reduction. If one limits the extent of the interrogating beam in the vicinity of the detected flaw then less material is involved, thus there are less sites for noise generation. Limiting of the beam can



Shear Wave - Polarization in the XZ plane



Shear Wave - Polarization in the XY plane



Longitudinal Waves

Figure 60 - Influence of polarization direction upon the amplitude response from a cylindrical hole oriented along the Y axis; propagation direction is 45° from the weldment face. The results for a longitudinal wave interrogation are also shown for comparison. See Figure 57 for direction notation. After Kupperman and Reimann (18).

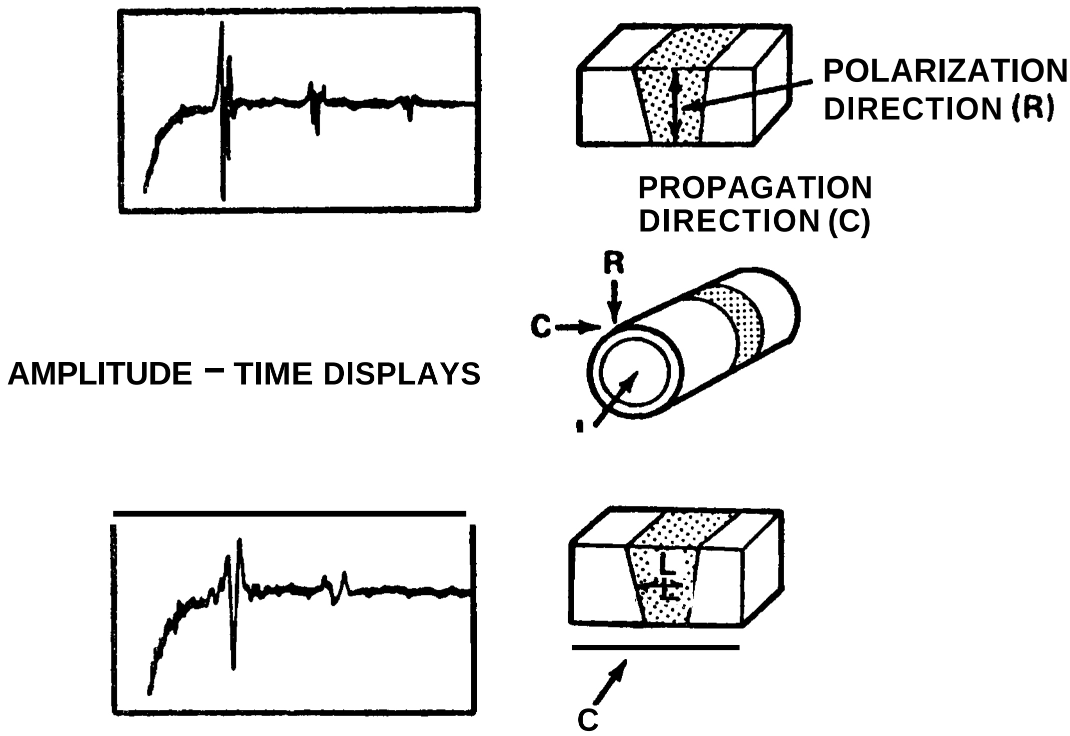


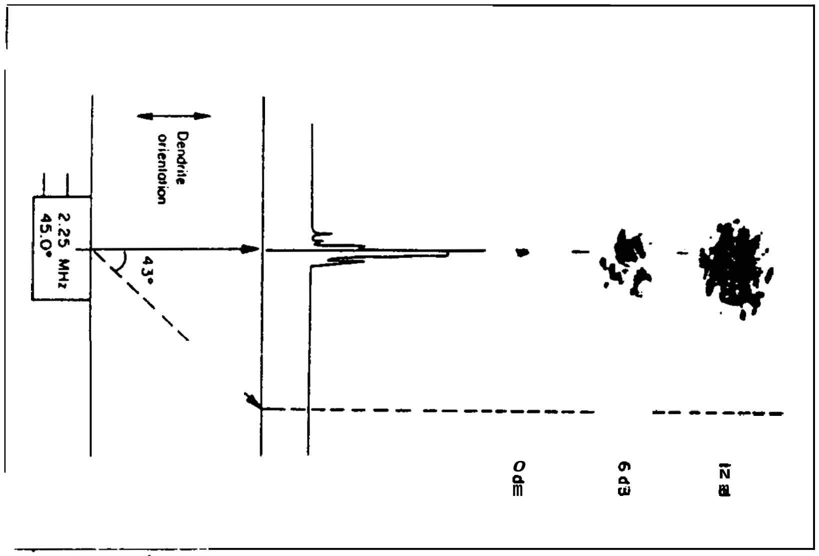
Figure 61 - Effect of shear wave polarization direction; propagation of the ultrasound is in the circumferential direction of an inconel/steel weld system. After Serabian (62).

	Amount of Damping		
Presentation	Heavy	Moderate	Undamped
R-F	1.88	0.8	---
Video	2.42	1.26	0.66

Figure 62 - Attenuation (db/in) noted in a weldment at 5 MHz for a variety of data presentations and transducer damping. After Serabian (75).

be accomplished by either extending the near field or by a focusing action. The interrogation frequency should be selected by experimental means. Other methods of reducing noise are based upon the random nature of noise. Probabilistic-statistical analysis techniques can sort out the random signals thereby enhancing the detecting ability.

Another difficulty produced by a columnar texture is the generation of false or spurious indications of flaws. H. Yoneyama, et al.,[68] studied the propagation of ultrasound in textured stainless steel weldments; their results are shown in Figure 63. In Figure 63, the C-Scan displays as noted by the through transmission technique are shown. Al electromagnetic transducer was used to eliminate any difficulties that may be presented by the angle in the resulting particle motion at the plane of the receiving transducer. In Figure 63a, the observed C-Scans in the base material are indicated at the specimen thicknesses generated by progressively machining 5mm slices. The latter demonstrates that the direction of the ultrasound in the base material is governed by the angle of entry. However, as shown in Figure 63b, the ultrasound in a weldment is diverted along the major axes of the columnar structure. The columnar structure is, in effect, acting as a wave guide for the ultrasound. The ensuing back reflections would be observed as indication emanating from flaws along the projected entry angle direction. G. Herberg, et al.,[69] describe futile attempts to destructively verify the existance of such spurious indications. Figure 63c displays the C-Scan presentations for the case where ultrasonic propagation is confined in a specimen that is totally weldment material. Again, it can be observed that the path of the ultrasound is along the columnar structure and not in the direction of the entry angle.



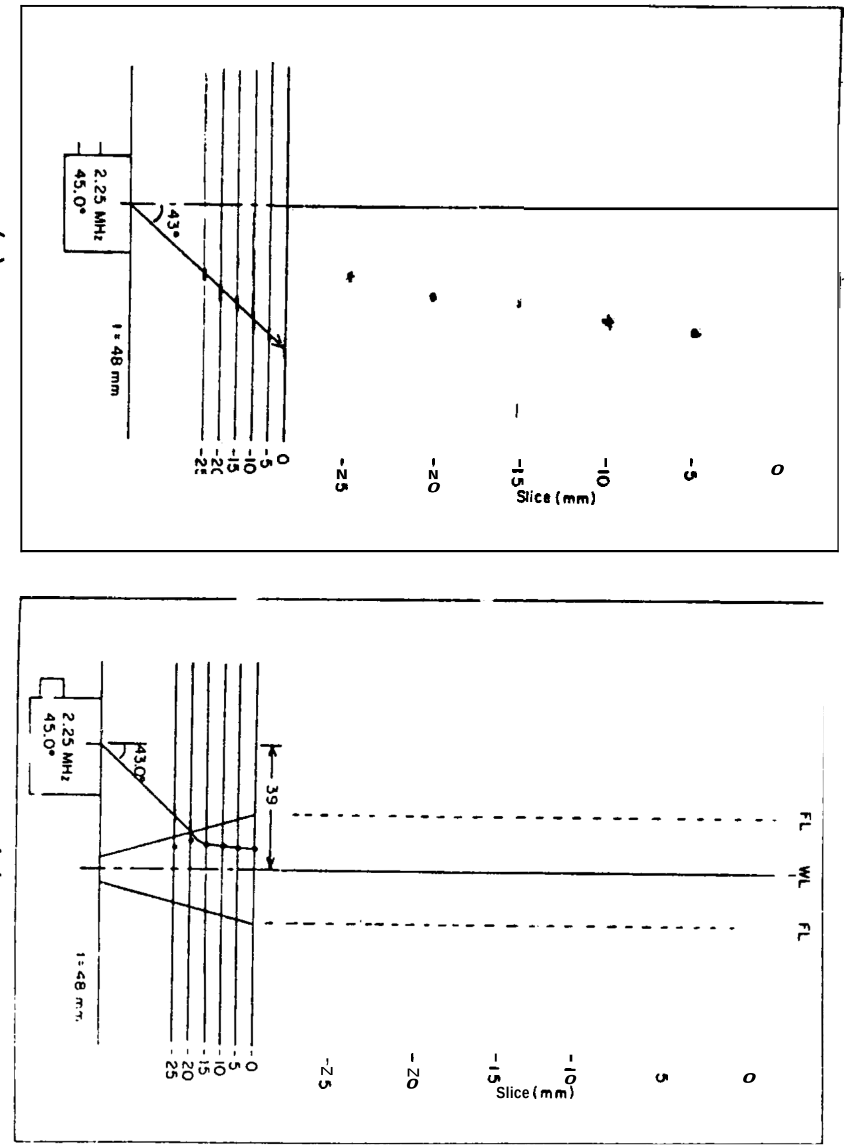


Figure 63 - Angle beam propagation within a weld system as indicated by through transmission scans at 5 mm slices. In (a) the results show that the path of the ultrasound within the base material is governed by the angle of the beam. In (b) and (c) the path is diverted along the major axis of the dendritic structure en3 is responsible for spurious indications. After Yonevama et al (68).