A Guideline of Ultrasonic Inspection on Butt Welded Plates

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A Guideline of Ultrasonic Inspection on Butt Welded Plates

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Abstract. This paper explained the procedure to carry out the ultrasonic inspection for single and double-V butt welded plates in detail by including the calculation of skip distance, stand-off, interpretation from plotting system, and the preparation of full inspection report as well. In addition, few inspections were compared on butt welded plate single and double-V to determine which is the most suitable, accurate and precise reading obtained. The comparisons were made between scheme answer from Sirim inspector, X-ray film, data that obtained from ultrasonic inspection and calculation by mathematical formulas and using plotting system. Mathematical formulas and plotting system was utilized to obtained the distance of stand-off (S_{off}) and skip distance, (S_{max}) whereas the plotting system were applied to locate the defects based on their S max and S off, and also to determine the depth, d and radius, r. The defects of single-V and double-V butt welding inspected by the ultrasonic technique were then compared with those obtained from the radiographic film while a good agreement was observed. However, the ultrasonic inspection proved to be much more sensitive than the radiographic inspection.

1. Introduction

The ultrasonic inspection method for non-destructive testing is principally based on beams of mechanical waves of short wavelength and high frequency transmitted from a probe and detected by the same or other probes. The attached oscilloscope display with a time base shows the time it takes for an ultrasonic pulse to travel to a reflector (a flaw, the back surface or other free surface) in terms of distance travelled across the oscilloscope screen. The height of the reflected pulse is related to the flaw size as seen from the transmitter probe. The relationship of flaw size, distance and reflectivity are complex, and a considerable skill is required to interpret the data from the display screen [1]. A typical pulse-echo UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and a display device. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (such as a crack) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. Knowing the velocity of the waves, travel time can be directly related to the distance that the signal travelled. From the signal, information about the reflector location, size, orientation and other features can be gained [2].

Ultrasonic flaw detection is generally based on a comparative technique. Using appropriate reference standards along with knowledge of sound wave propagation and generally accepted test procedures, a competent operator is able to identify specific echo patterns corresponding to the echo response from good parts and from representative flaws. The echo pattern from a test piece may then be compared to the patterns from these calibration standards to determine its condition [3]. The common defects or flaws found in a welded plate or pipe are lack of fusion (LOF), slag, porosity, lack of penetration (LOP), and cracks. An echo of over penetration easily can be interpreted as a defect, however, only realistic defects or flaws are considered as defects. Therefore, a good understanding of the nature of welding defects is most important before carrying out the inspection. Sometimes, it is difficult to distinguish between side wall crack and slag inclusions. Basically, defects can be categorised as three types as crack like defects (centre crack, side wall crack and LOF), volumetric defect such as porosity and slag and defect in the bottom of weld (LOP and root crack)[4].

2. Experimental Procedure

For ultrasonic inspection, an ultrasonic machine manufactured by Sonatest, with designation transducer of SLC 4-20 (TO 30633), SMA 4-60 (S 2074) and SMA 4-45 (S 2065) was utilized for the inspection. This section explains the inspection of the welded plate using normal probe, angle probe with half and full skip distance, calculation, plotting system and compared with X-ray film.

2.1. Normal Probe

In this inspection method on a parent metal, a normal probe with frequency of 4 MHz was based on the thickness as shown Table 1 below. The parent metal of single-V and double-V welding was inspected for presence of any delamination as illustrated in Figure 1. Delamination may occurs during the manufacturing process due to layer de-bonding or stripping between layers of hot-mix asphalt. This can cause distresses such as longitudinal cracking in the wheel path and tearing in the surface [5].

Table 1. Parent metal thickness, probe and the frequency

Thickness of parent metal (mm)	Type of probe	Frequency (MHz)
Up to 28	Twin crystal	2 to 5
Over 28 to 40	Normal probe	2 to 5

The velocity of the longitudinal waves of steel was fixed to be 5930 mm/s. The test range was calibrated with a test ranges as given in Table 2 or in accordance to the procedure for the plate inspection using V1 Block. The selected test sensitivity for straight beam probe was primary reference echo level (PRE) was set for first back wall echo to 80% full screen height (FSH) from the sound part of the welded plate. The scanning sensitivity and evaluation sensitivity is illustrated in equation (1) and (2). The scanning sensitivity was set to be 23.5 dB for both single-V and double-V welded plate by recording the threshold as 80% of first back wall echo and the range was 100 mm. A masking tape was located along the welding region by covering the welding cap. Hence, any indications of defect can be marked on the masking tape as shown in Figure 1.

The evaluation sensitivity is the PRE value by reducing the gain from scanning sensitivity to PRE value if there is any suspected indication presence during the scanning.

$$\text{Scanning sensitivity} = \text{PRE} + 6\ \text{dB} \tag{1}$$

Evaluation sensitivity = PRE (2)

Table 2. Parent metal thickness and the test range

Parent Metal thickness T (mm)	Test Range (mm)
Up to 22	50
Over 22	100

Figure 1. Scanning of parent metal with normal probe

2.2. Angle Probe

The velocity of the shear waves of steel was set to be 3230 mm/s. The angle of beam was selected according to the parent metal thickness as shown in Table 3. IIW or known as V2 block was used for the sweep the range of calibration in addition to ASME basic calibration block was used for the PRE setting. The thickness of the basic calibration block was selected according to the thickness of plate as shown in Table 4. Additionally, the sweep range was calibrated to a test range as indicated in Table 5.

Table 3. Thickness of parent metal, suitable angle and frequency

Parent metal thickness T (mm)	Angle (°)	Frequency (MHz)
Up to 15	60 and 70	2 to 5
Over 15 to 30	45,60 and 70	2 to 5
Over 30 to 40	45 and 70	2 to 5

Table 4. Thickness of parent metal and the block thickness

Parent metal thickness (mm)	Block Thickness
Up to 28	19 mm
Over 28 to 40	38 mm

Table 5. Test range

Parent Metal Thickness (mm)	Test Range (mm)
Up to 15	100
Over 15 to 40	100-200

Before scanning on welded plate, the Distance Amplitude Correction (DAC) curve should be plotted. DAC provides a means of establishing a graphic reference level sensitivity as a function of sweep distance on the A-scan display [6]. The sensitivity of angle was set by referring to ASME basic calibration block for PRE level as illustrated in Table 3. The threshold was recorded to be 20% DAC. Any indication above 20% of DAC will be evaluated as shown in Figure 2. For 60^{o} angle probe, the scanning sensitivity as in equation (3) and evaluation sensitivity as in equation (4) was set to be 50.5 dB and 44.5 dB respectively for single-V as well as double-V welded plate. However the defect indications were double confirmed by using angle probe 45^{o} by setting the scanning sensitivity and evaluation to 47 dB and 33 dB respectively.

Scanning sensitivity = DAC + 6 dB + Transfer loss (3)
Evaluation sensitivity = PRE + Transfer loss (4)

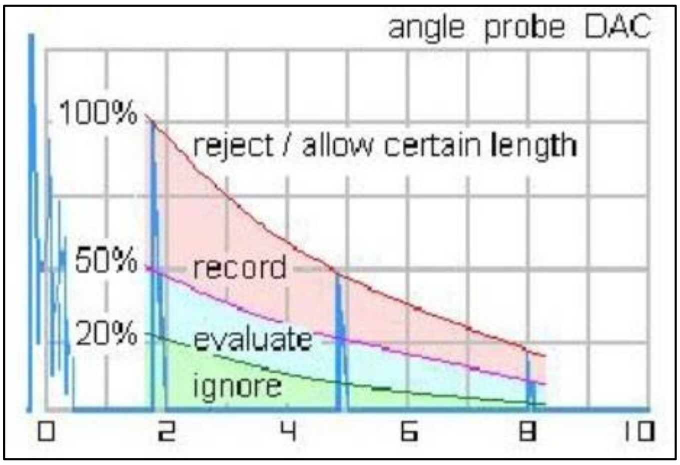

Figure 2. Evaluation and decision making of DAC [7]

2.2.1. Half Skip Distance.

A welded plate as labelled with symbol ^ as shown in Figure 3 indicate where the inspection should begin. The left side is assumed as A(-ve) whereas the right side assumed as B(+ve) region. Half skip distance measured based on equation (5) for critical root scanning by selecting suitable probe according to the thickness of the single-V welded plate. This critical root scanning can be done as lateral scanning along the calculated half skip distance path by using magnetic tape as shown in Figure 4. Nevertheless, for double-V welded plate ¼ skip distance as illustrated in equation (6) was examining as critical root scanning. The couplant a mixture of machine oil and grease was utilized as intermediate liquid between the probe and welded plate.

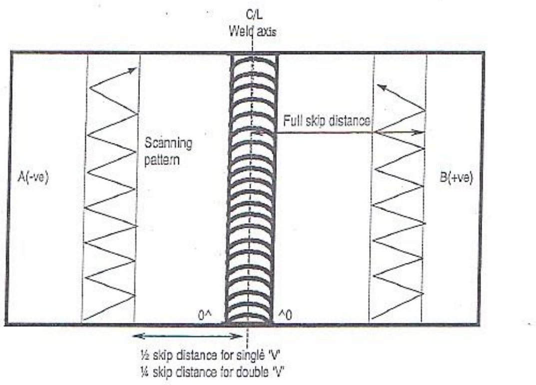

Figure 3. Examination Butt Weld with angle beams.

Figure 4. Lateral scanning for critical root scanning.

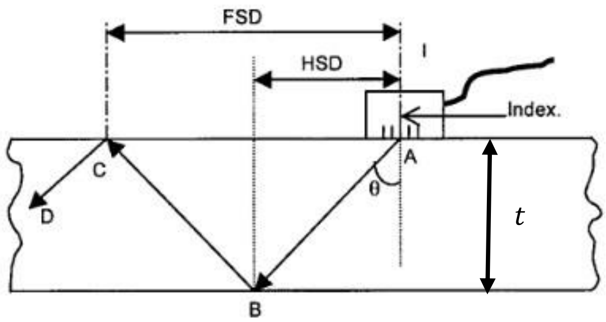

Figure 5. Skip Distance [8]

$$\text{Half skip distance, HSD} = t \times \tan\emptyset \qquad (5)$$

$$\text{Quater skip distance, ¼ SD} = \frac{t}{2} \times \tan\emptyset \qquad (6)$$

$$\text{Full skip distance, FSD} = 2t \times \tan\emptyset \qquad (7)$$

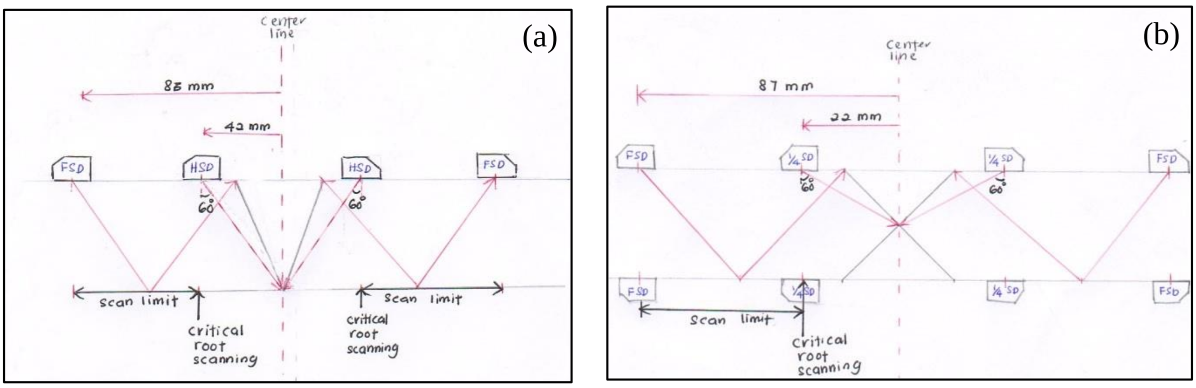

Figure 6. Schemetic of skip distance of probe 60^{o} movement for (a) Single-V and (b) Double-V

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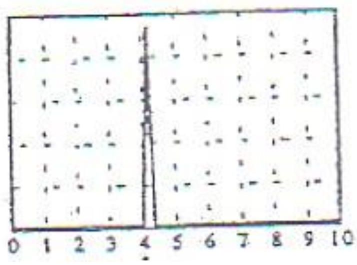
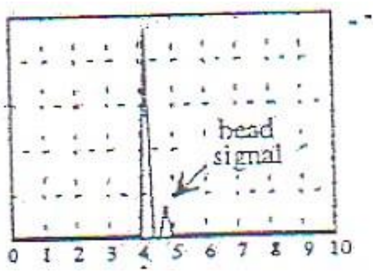
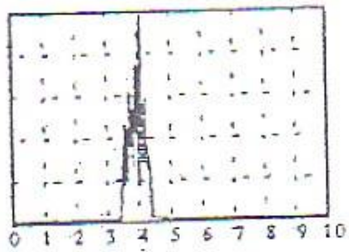
2.2.2. Full Skip Distance

Full skip is the distance travelled when the angle beam has travelled down then up as shown in Figure 5. A zig-zag scanning as shown in the Figure 3 is carried between the distances of half or quarter skip distance and full to inspect any defects on the welded region the single-V and double-V welded plates respectively. Inspection on ultrasonic can be on both sides (backside measurement) of double-V welded plate as shown in Figure 6. Table 6 illustrates the type of defects and their description. Table 7 illustrates the scanning pattern for confirming the types of defect that is obtained by observing the amplitude pattern by manipulated with the scanning pattern.

Table 6. Types of defect indication for ultrasonic

Types of defects	Description	HSD FSD	Diagram of echo[9]
Lack of penetration (non-volumetric)	• High amplitude of both side (A and B) of welded plate • Rapidly decreasing in amplitude on rotational scanning	HSD for singleV ¼ SD for double-V	
Lack of fusion (non-volumetric)	• High amplitude • Rapidly decreasing in amplitude on the swivel and orbital scanning • Remain the amplitude when lateral	Between HSD and FSD	
Crack (non-volumetric)	• Crack can be located in toes crack, heat affected zone, center of weld, and at root • High amplitude and multi-faceted reflector • Signal rise and fall on the swivel and lateral scanning • Decrease in amplitude if orbital scanning	Between HSD and FSD	

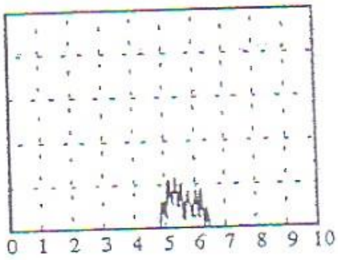
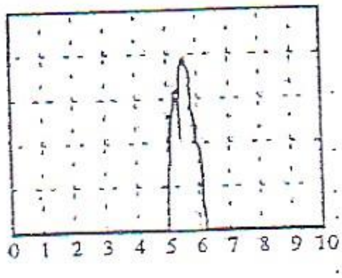
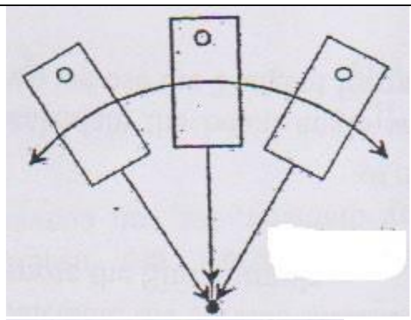
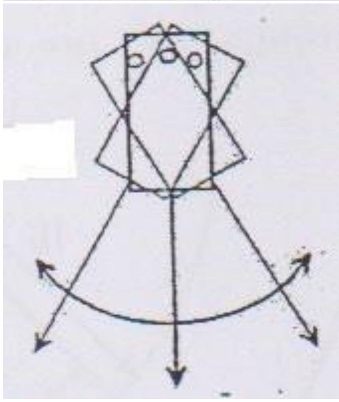
Porosity (volumetric)	• Low amplitude • Giving multiple signals with a wide • Signal maintain on orbital	Between HSD and FSD	
Slag (volumetric)	• Signal contains numerous half cycles and rounded peak • Signal appears to fall as the beck edge rises	Between HSD and FSD	

Table 7. Scanning Pattern of Ultrasonic

Scanning patterns	Description	Diagram [9]
Orbital scan	• Probe is manipulated through an arc movement whist maintaining the beam focused on a reflector. • Suitable to identify porosity where the signal is maintained on an orbital scan.	
Swivel scan	• Probe is rotated on the spot, effectively scanning the beam around it. • Used to identify multi-faceted, planar or multiple defects	

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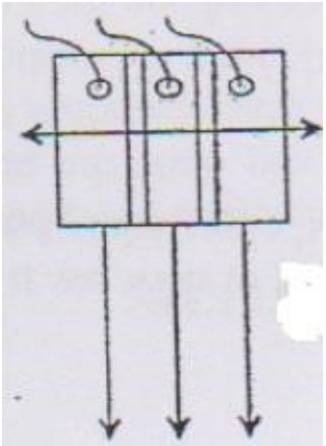
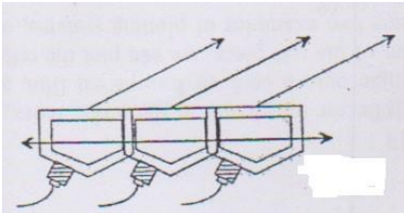
Lateral scan	• Probe is moved sideways along a fixed line. • Used for critical root scanning of single-V weld or for sizing the length of a defect longitudinally.	
Depth scan	• Probe is moved back and forth in the direction of the beam. • As in locating the position of a defect when maximising the signal off a transverse hole to set sensitivity.	

2.2.3. By Calculation

When performing an angle beam inspection, it is important to know where the sound beam is encountering an interface and reflecting. The reflection points are sometimes referred to as nodes. The location of the nodes can be obtained by using the trigonometric functions or by using the trigonometric based formulas as shown in equation (8) and (9). Stand-off is referring the distance of probe index to the center line, however surface distance or known as skip distance is the distance from the probe index where the sound beam returns to the surface.

Stand-off of half skip, S_{off} = t x tan Ø (8)

Surface distance, S_{max} = t / cos Ø (9)

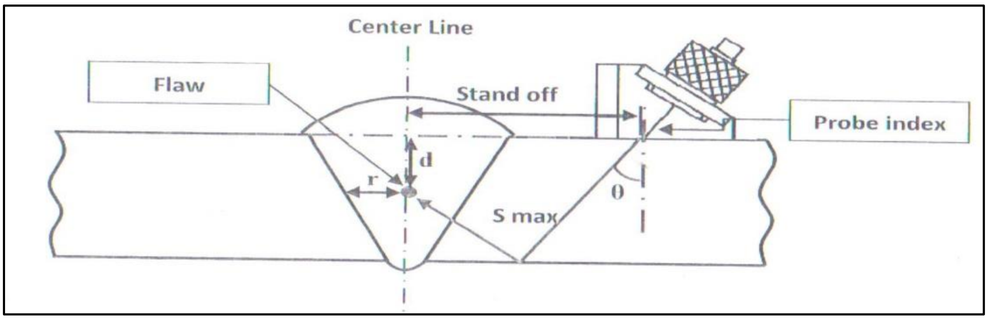


Figure 7. Location of probe

2.2.4. Plotting Card

In angle probe scanning plotting systems are used for projecting defect depths and positions in relation to the probe index by applying the beam path, read from the screen (CRT time base) and the stand-off or surface distance from a reference datum on the welded plate. By drawing probe angle onto a plotting card, while overlapping the reflector welding portion on the plotting card based on standoff and surface distance to indicate the position of the defects as shown in Figure 8. The exact locations labelled as 1, 2 and 3 are supposed to reflect on the mirror line as shown in Figure 9 and 10.

Once the locations in the tracing paper as in Figure 9 and 10 are marked, Figure 11 should be filled up. Figure 11 describes the angle probe that are used, types of defects that are encountered, value of dB above the 100% of DAC curve, value of stand-off, and maximum surface distance. The description of sizing of the defects as shown in Figure 7 are as below:

L = length of the defects
d = depth of the defects from upper surface
r= radius of the defect from centre line (-ve for left and +ve for right)
q = length from datum as marked as ^ as shown in Figure 3

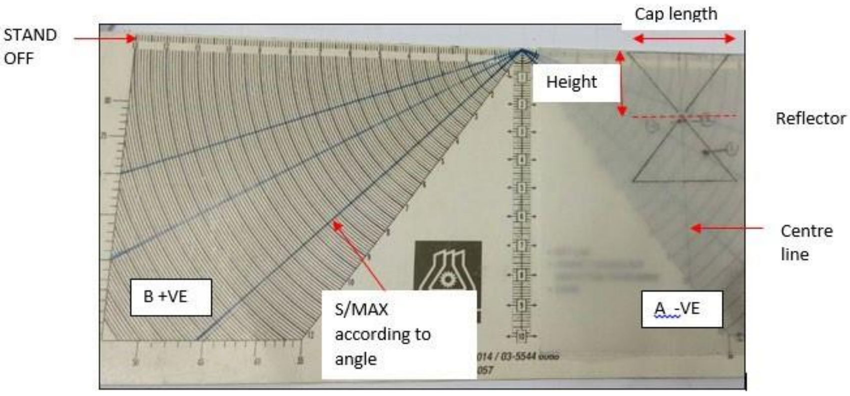


Figure 8. Plotting Card

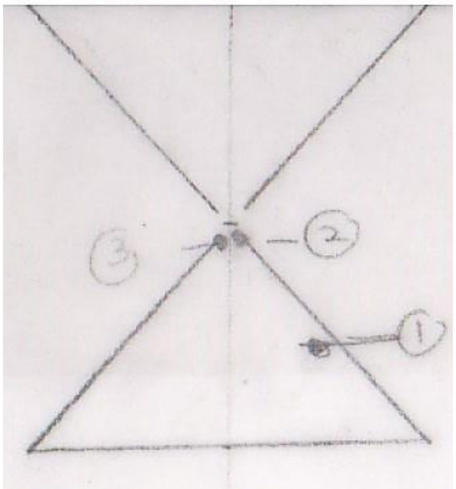


Figure 9. Location of defects in Single V.

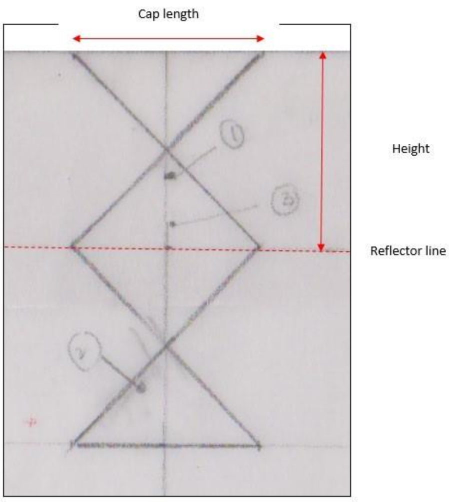
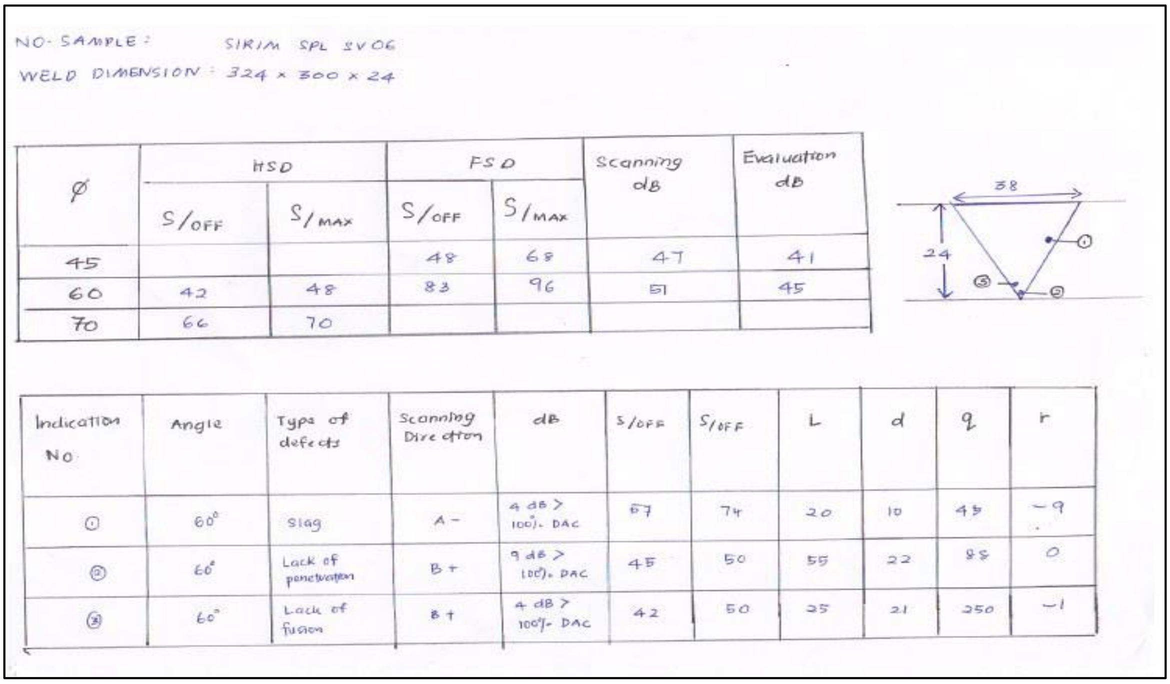


Figure 10. Location of defects in Double V.



NO. SAMPLE : SIRIM SPL SV 06
WELD DIMENSION : 324 x 300 x 24

ø	HSD		FSD		Scanning dB	Evaluation dB
	S/OFF	S/MAX	S/OFF	S/MAX		
45			48	68	47	41
60	42	48	83	96	51	45
70	66	70				

Indication No	Angle	Type of defects	Scanning Direction	dB	S/OFF	S/OFF	L	d	q	r
①	60°	slag	A −	4 dB > 100% DAC	57	74	20	10	45	−9
②	60°	Lack of penetration	B +	9 dB > 100% DAC	45	50	55	22	85	0
③	60°	Lack of fusion	B +	4 dB > 100% DAC	42	50	25	21	250	−1

Figure 11. Recording the data in the table

2.2.5. X-ray

An X-ray film in SPL SV 06 was viewed using film viewer and the defects are clearly seen by switching of the power and sizing could be done using ruler to measure the length of the defect, L and from datum, 0.

Figure 12. Result of X-ray for (a) Single-V and (b) Double-V

3. Result and Discussion

Table 8 shows the signal of defects for single-V that was obtained from SIRIM scheme by inspectors and compared with signal that was obtained by ultrasonic inspection. Basically signal that obtained by both parties are morally the same. It is also important to note that when using shear waves to know where along the probe the beam enters probe index. The probe index position relative to some datum on the specimen and the exact beam angle allows to calculating the horizontal and vertical distances.

Table 8. Defect Signal of Single V

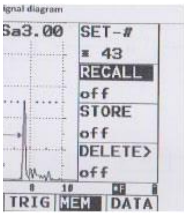
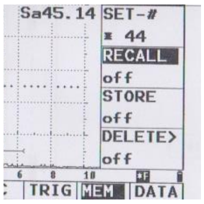
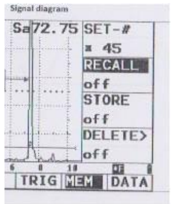
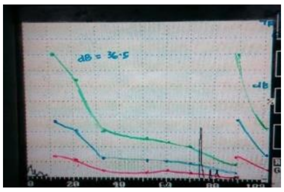
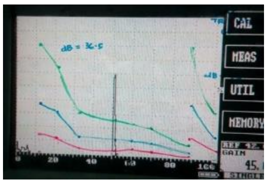
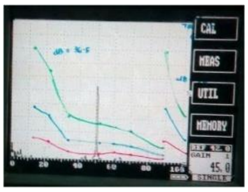
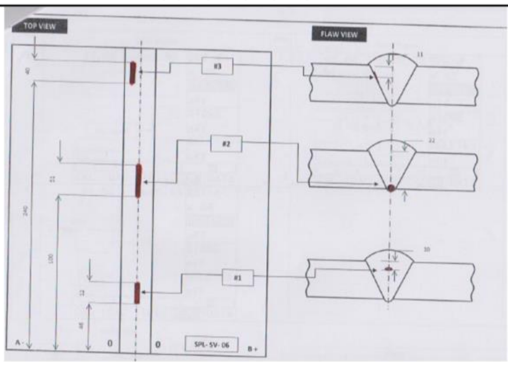
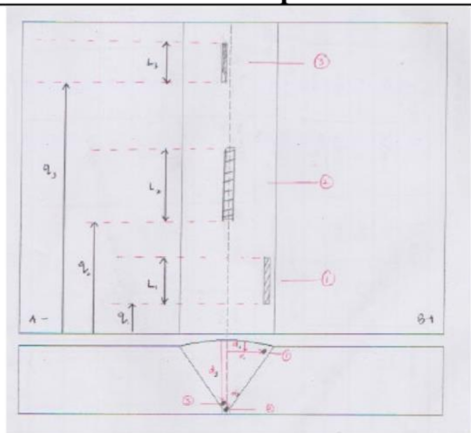
Location	**1**	**2**	**3**
Type Scheme Sirim	Slag 	LOP 	LOF 
Location	**1**	**2**	**3**
Type Ultrasonic Inspection	Slag 	LOF 	LOP 

Table 9 shows the defects location and the sizing by comparison which is made from SIRIM scheme with ultrasonic inspection. In this case, both parties are using angle probe, 60°, however for defect no 2 and 3, though we used opposite direction of scanning, it did not influence the accuracy of reading that was obtained. The data of sizing basically same and do not have much significant. The difference in length of scheme was 42% while ultrasonic inspection was 4% if compared with result of X-ray. In general there are three techniques that can be utilized for sizing the defect such as applying maximum amplitude, 6 dB drop or 20 dB drop. For ultrasonic inspection of these welded plate sizing was based on 20 dB drop was used throughout the inspection. However, all these three techniques should give the same reading. However, the hand pressure on the probe might influence the reading as well.

Table 9. Diagram and sizing of defects in Single-V welded plate

	Scheme of SIRIM	**Ultrasonic inspection**
Diagram		

Sizing

Scheme of SIRIM:

No.	L	q	d	r
1	12	46	11	7
2	51	100	22	0
3	40	240	10	0

Ultrasonic inspection:

No.	L	q	d	r
1	20	45	10	9
2	55	88	22	0
3	25	250	21	-1

On the other hand, Table 10 shows the signal of defects for double-V that was obtained from SIRIM scheme by inspectors and compared with signal that was obtained by ultrasonic inspection. Basically signal that obtained by both parties are morally the same.

Table 10. Defect Signal of Double-V

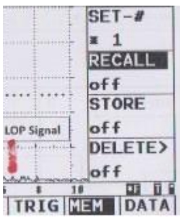
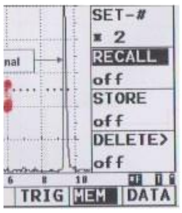
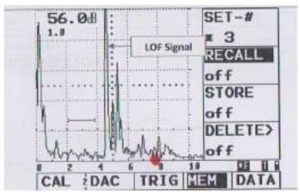
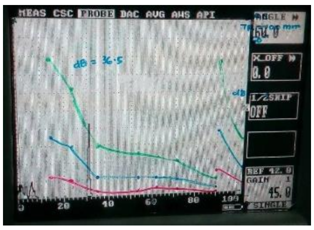
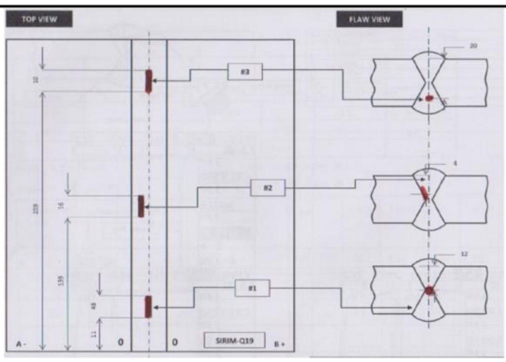
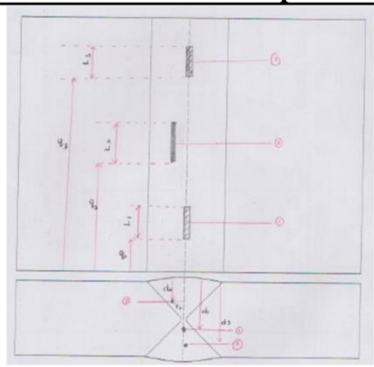
Location	**1**	**2**	**3**
Type Double Plate	Slag 	LOF 	LOP 
Location	**1**	**2**	**3**
Type Double Plate	Slag 	LOF 	LOP 

Table 11. Diagram and sizing of defects in Double-V welded plate

	Scheme of Sirim	Ultrasonic inspection
Diagram		

Sizing — Scheme of Sirim

No.	Flaw type	Angle, Ø	Scanning area
1	Slag	60	A-
2	LOF	60	B+
3	LOP	60	B+

No.	l	q	d	r
1	11	48	12	0
2	16	139	4	6
3	10	259	20	0

Sizing — Ultrasonic inspection

No.	Flaw type	Angle, Ø	Scanning area
1	Slag	60	A-
2	LOF	45	A-
3	LOP	60	B+

No.	l	q	d	r
1	20	65	15	0
2	20	143	8	-3
3	17	250	22	1

Similarly, defect length is usually a significant criteria for accept/reject of a weld. Since most codes acceptance criteria for ultrasonic inspection are conversions of radiographic acceptance criteria, the defect lengths are based on workmanship, therefore they are conservative. Typically 10-12mm would be the maximum allowable length for some flaw types. However, for short flaws, the normal dB drop method measures only beam width not defect length.

Table 12. A comparison between few techniques

	Single-V			Double-V		
	Defect 1	Defect 2	Defect 3	Defect 1	Defect 2	Defect 3
	Slag	LOP	LOF	Slag	LOF	LOP
	Length (mm)			Length (mm)		
Data ultrasonic inspection	20	55	25	20	20	17
Scheme of SIRIM	12	57	40	11	16	10
X-ray	21	54	Not detectable	25	20	10

Scheme from SIRIM	12	51	40	11	16	10

A comparison of data that was obtained from X-ray, ultrasonic inspection, calculation by mathematical equation, and plotting system was carried out. Based on the Table 8 and Table 9 for LOP and LOF giving maximum amplitude due to the non-volumetric region**.** Based on X-Ray result on butt welded single-V film, the lack of fusion was not clearly visible. It may be due to the angle or direction of the X-ray source. X-ray is supposed to be carried at ± 30^{o} to detect side wall fusion which is a volumetri**c** defect. Therefor X-ray should be taken at few angles to obtain an accurate reading. Indeed ultrasonics are very sensitive to these types of defects. This shows that an ultrasonic test is most suitable inspection to detect the defect by covering all the region of welding by angle beam, even though it's consuming time compared to X-ray. Conversely, in X-ray examination there is potential to miss defects.

4. Conclusion

Defect sizing is very essential for performing structural integrity of a material. The defects of single-V and double-V butt welding inspected by the ultrasonic technique were then compared with those obtained from the radiographic film. A good agreement was observed. It exists in different ultrasonic sizing techniques based on signal amplitude but the data cannot be stored. All the indication will appear on the display so that instant interpretation have to be done. Ultrasonic is much more sensitive but it requires a high degree of skill in interpreting pulse-echo patterns. However, a permanent record is not readily obtained when compared with radiography. On the other hand, radiography defect indication is recorded on film hence giving a permanent record. However, skill is needed for selecting the best angles of exposure and interpreting indications. At the same time, strict safety precautions must be observed. It's not generally suitable for fillet welding inspection.

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