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TIME OF FLIGHT DIFFRACTION (TOFD) TECHNIQUE FOR ACCURATE SIZING OF SURFACE BREAKING CRACKS

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Abstract

This paper deals with an experimental study for evaluation of TOFD technique for determination of size of the surface breaking cracks. The study was confined to simulated cracks. The steel test blocks used for the study contained 0.5mm wide vertical slits of various heights ranging from 0.91mm to 30mm. Another set of blocks contained inclined slits (10°, 15°) inclination of various heights ranging from 2.56mm to 19.82mm. Both the vertical and inclined slits were opened to the top surface. TOFD equipment Model MICROPLUS of M/S AEA Technology, UK with manual scanner along with longitudinal angle beam probes of 45° - 4MHz were used for the study. The blocks were scanned along the slits / defects and across the slits. The scanned images were analysed for the sizing. The results of the study indicated an average error of ±0.13 for depth in vertical slits and ±0.05 for inclined slits whereas the average error in length measured was ±0.36mm for vertical slits and ±0.29mm for inclined slits. However difficulty was experienced using TOFD to size defects extending less than about 2mm depth. This is due to the presence of the lateral wave, which obscures the tip-diffracted signals from the defects close to the surface and also due to the inherent lack of time resolution near the surface.

Keywords: Time of flight diffraction, through thickness height, surface breaking cracks.

1.0 Introduction

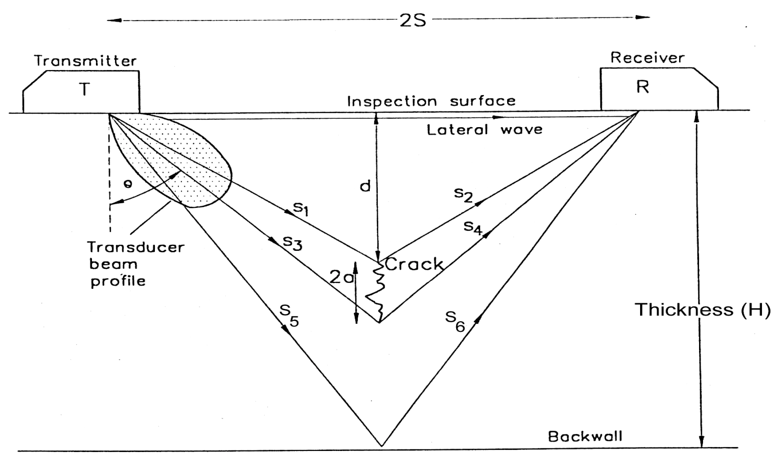
The ultrasonic testing techniques are extensively employed for detection and characterisation of flaws during manufacturing and in-service inspection of critical engineering structures and systems. These techniques assure the integrity and reliability of the components. The recent developments in the ultrasonic inspection technology, based on the need for fitness for purpose has resulted in a reliable and accurate technique called a Time Of Flight Diffraction Technique (TOFD) [(1,2)]. This method uses the phenomena of ultrasonic diffraction. The use of the phenomena of ultrasonic diffraction has distinct advantages in the sizing of defects, particularly the crack like planar defects. Diffracted wavefronts effectively originates at the crack tips [(3, 4)]. The difference in time of flight of wavefronts carry the information on the spatial relationship of the crack tips and hence, the extent of the crack. TOFD is a single pass operation, not amplitude dependent and very accurate for sizing of vertical defects. However the technique requires access to both the sides from one surface. [(5)] TOFD requires specialist knowledge and sophisticated technology to effectively apply. This technique is found to be substantially more accurate than conventional pulse echo techniques, which is based on echo amplitude and requires correction for beam size reflectors. Techniques are not reliable for sizing of vertical cracks, whereas the ultrasonic techniques based on transit time are reasonably accurate but require access from several sides and not all new surfaces will provide good reflection. The DGS system is simple go / no-go system which can be applied to different shapes but requires special curves and gives no indication of vertical extent of the defects [(5, 6)].

The authors have carried out an experimental study to understand what TOFD technique could achieve so far as the sizing of vertical cracks are concerned.

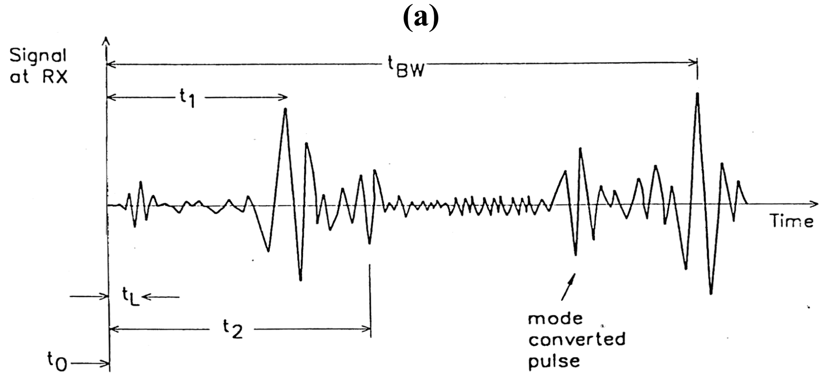
2.0 The basic TOFD technique

The TOFD technique is based on diffraction of ultrasonic waves on tips of discontinuities instead of geometrical reflections on the interface of the discontinuities. The difference in the time of flight in the diffracted wave fronts carry the information on the spatial relationship of the defect tips and hence the extent of the defect [(7)]. Since the technique relies on the detection of the forward scattered diffracted signals originating from the flaw edges, precise measurement of the flaw size, location and orientation is possible. The use of the phenomena of ultrasonic diffraction has distinct advantage in sizing of crack or crack like planar defects[(8, 9)]. The technique employs ultrasonic longitudinal angle beam probes (one as a transmitter and other as a receiver) widely spread sound beam to cover the whole defect. The transmitting transducer T emits a short burst of ultrasound into the steel plate. This energy spreads out as it propagates into a beam with some definite angular variation. Some of the energy is incident on the crack tip (O & O') and is scattered by it. Scattering from the edge of the cracks, called diffraction, causes some fraction of the incident energy to travel towards the receiving transducer R. If the crack is big enough, then the signals from the two extremities of the crack will be time resolved. In addition to these two signals, there will be some energy, which arrives at the receiver directly from the transducer by the shortest possible path just below the surface of the component and an echo from the back wall as shown in Figure: 1(a). Such a set of actual signals is displayed in the lower part of Figure – 1(b). In the example, the transducers were moved at constant separation, in the vertical plane, over a defect perpendicular to the plane. The signals appearing are from the top of the figure to the bottom, the lateral wave, signals from the top tip of the crack (O) and bottom tip of the crack (O') and finally the back wall echo [1, 10, 11].

Longitudinal waves are used since the diffraction is stronger compared to shear waves. The two diffracted signal at the crack tip are generated with 180° phase shift. The distance between two signals on the time scale is non-linear[12]. In addition to diffracted waves there is a lateral wave which runs beneath the surface and the back wall echo reflects the bottom surface of the test object and reach to the receiver as shown in the Figure -1.



(a)



(b)

Figure -1 Basic principle of TOFD technique for estimation of through thickness height of the crack

3.0 Mathematical model for crack sizing

To calculate the through-wall size and depth from inspection surface, Pythagoras theorem is used [1, 12]. Under the following assumptions

a). Crack is oriented in a plane perpendicular to both the inspection surface and the line joining the transmitter and receiver along the inspection surface.
b). Crack is midway between the transmitter and receiver.

The arrival times of various signals are:

(i). The first arrival time from the lateral wave (L) signal to the receiver

$$t_L = \frac{2S}{C}$$

(ii). The second arrival time from the top-tip diffracted (t_1) signal to receiver

$$t_1 = \frac{2\sqrt{(d^2 + S^2)}}{C}$$

(iii). The third arrival time from the bottom-tip diffracted (t_2) signal to receiver

$$t_2 = \frac{2\sqrt{(d+2a)^2 + S^2}}{C}$$

(iv). The fourth arrival time from the back wall (t_{bw}) echo to receiver

$$t_{bw} = \frac{2\sqrt{H^2 + S^2}}{C}$$

(v). The depth (d) of the tip of the crack from the inspection surface

$$d = \frac{1}{2}\sqrt{C^2 t_1^2 - 4S^2}$$

(vi). The through-wall extent (2a),

$$2a = \frac{1}{2}\sqrt{C^2 t_2^{\,2} - 4S^2} - d$$

(vii). The value of the separation of probes (2S),

$$2S = \sqrt{C^2 t_{bw}^{\,2} - 4H^2}$$

(viii). The probe delay, t_0 can be determined from either the lateral wave or back wall reflection (transit times t_1 & t_{bw}) [13] as

$$2t_0 = \frac{t_1 - 4S}{C} \qquad \text{(lateral wave)}$$

$$\& \qquad 2t_0 = \frac{t_{bw} - 2(2S^2 + H^2)^{1/2}}{C}$$

Where

2S is the distance of separation of the two probes
C is the velocity of the longitudinal wave
d is the position below the inspection surface
2a is the through wall extent of the crack
H is the thickness of the material.

4.0 Experiments using TOFD technique

An experiment was carried out to understand what TOFD technique could achieve so far as the sizing of vertical surface breaking cracks are concerned. TOFD equipment Model MICROPLUS of M/S AEA Technology, UK with manual scanner along with longitudinal angle beam probes of 45° - 4MHz were used for the study. The study was confined to simulated cracks. The steel test blocks used for the study contained 0.5mm wide vertical slits of various heights ranging from 0.91mm to 30mm. Another set of blocks contained inclined slits (10°, 15°) inclination of various heights ranging from 2.56mm to 19.82mm. Both the vertical and inclined slits were opened to the top surface. The slits were all smooth and varied in through wall extent. The actual dimensions of the block, the location and size of the slits is shown in Figures 2 & 3 and Table 1 & 2. Slits are really quite good models of cracks as diffraction is considered [14].

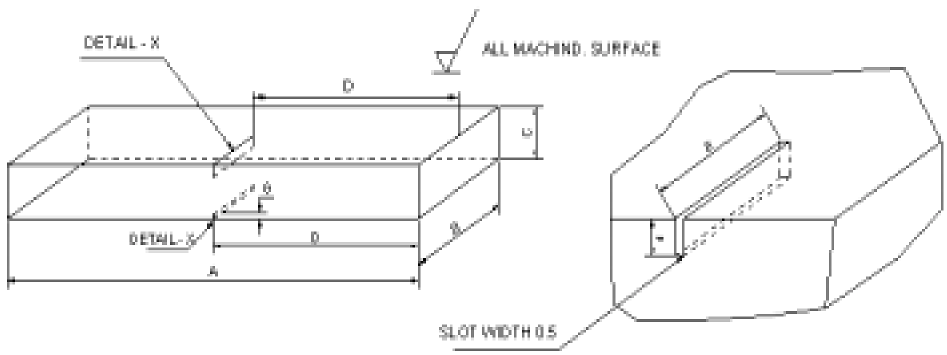


Figure 2: Schematic diagram of the steel blocks showing the location & size of the vertical slits

Table -1 Dimensions of the blocks containing vertical slits

VERTICAL SLITS							
DIM / BL No	A	B	C	D	E	F	G
BL.1	248	39.8	27	124	20	4.82	0.91
BL.2	247.5	39.8	27	128.75	25	9.9	1.82
BL.3	200	48.5	39	100	30	19.98	2.89
BL.4	250	39.10	29.3	125	25	14.95	3.874

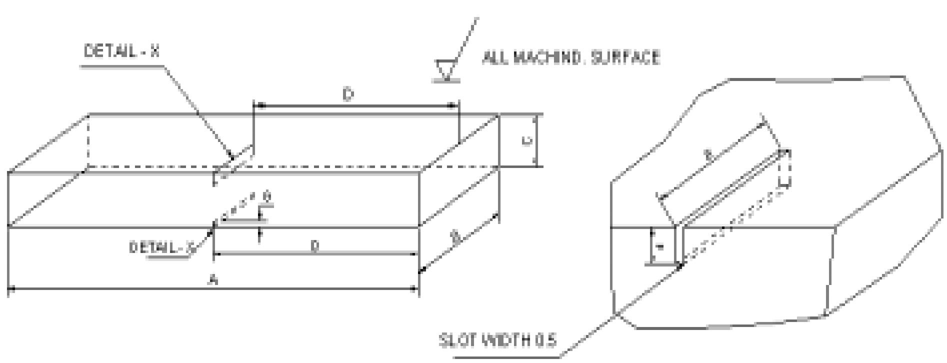


Figure 3: Schematic diagram of the steel blocks showing the location & size of the inclined slits

Table – 2 Dimensions of the blocks containing inclined slits

INCLINED SLITS								
DIM / BL No	A	B	C	D	E	F	G*	θ^0
BL.5	231.7	37	54.2	115.85	25	5.07	2.56	15
BL.6	130.3	37.4	54.4	115.15	20	9.83	7.39	15
BL.7	225.3	41.3	112	112.65	25	14.8	12.32	10
BL.8	300.6	41	98.7	150.3	25	19.82	17.3	10

5.0 Through - wall estimation of surface breaking cracks

In case of surface breaking cracks, if the top tip of the crack is opened to the scanning surface, the lateral wave is perturbed and the through wall extent of the crack can be estimated by locating the depth of the bottom tip of the crack from the scanning surface by the equation, [2]

$$d = \sqrt{\frac{(C\,\Delta t)^2}{4} - S^2}$$

Where Δt is transit time in the component.

The through wall extent of the cracks opened to the opposite surface of the scanning surface can be estimated by locating the top-tip of the crack (d) and subtracting from the total thickness of the specimen (H - d).

6.0 Observations

The experimental observations with respect to through thickness height and length of the simulated cracks are shown in Table –3 and & the details of the cross-sectional size of the simulated cracks are shown in Table – 4. The Figures - 5 & 6 gives the graphical representation of the actual Vs estimated height of the slits and Figures 9 & 10 shows the actual images of some of the vertical and inclined slits. Table – 5 shows the consolidated results of the experiments. Figures -7 & 8 gives the aspect ratio (actual Vs estimated) for vertical and inclined slits respectively.

Table – 3 Estimation of through thickness height / length of cracks

Block No.	Thickness (mm)	Actual slit height (mm)	Slit tip depth from scanning surface (mm)	TOF difference Δt (μ sec)	Measured height (mm)	Error in height (mm)	Actual slit length (mm)	Measured length (mm)	Error in length (mm)
VERTICAL SLITS									
01.	27	0.91	26.09	-	-	-	20	19.84	-0.16
		4.82	4.82	-	4.716	-0.104			
02.	27	1.82	25.18	0.2812	1.9397	+0.1197	25	24.9	-0.1
		9.9	9.9	1.3438	9.42	-0.48			
03.	39	2.89	36.11	0.1406	2.6777	-0.213	30	29.45	-0.55
		19.98	19.98	2.9688	19.949	-0.031			
	48.5	30	30	2.4219	29.83	-0.17	19.98	19.53	-0.45
04.	29.3	3.874	25.426	5.2969	3.85	-0.024	25	24.04	-0.96
		14.95	14.95	2.0312	14.830	-0.12			
	39.1	25	25	4.7187	24.837	-0.163	14.95	15.03	+0.08
INCLINED SLITS									
05.	54.2	2.56	51.64	-	2.56	0	25	25.84	+0.84
		5.07	5.07	0.1486	5.4506	+0.3806			
06.	54.4	7.39	47.01	7.7188	7.215	-0.175	20	20.43	+0.43
		9.83	9.83	0.8584	9.4971	-0.3329			
07.	112	12.32	99.68	2.5312	12.294	-0.026	25	24.94	-0.06
		14.8	14.8	3.3593	14.942	+0.142			
08.	98.7	17.3	81.4	1.75	17.114	-0.186	25	24.93	-0.07
		19.82	19.82	3.2812	19.584	-0.236			

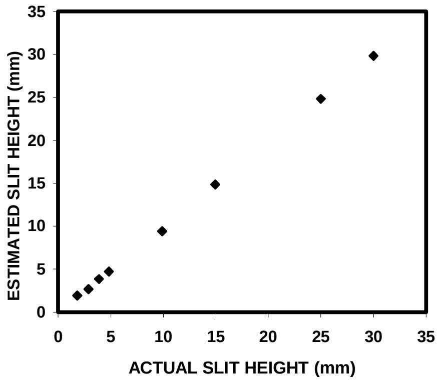


Figure - 5 Estimation of through thickness height for vertical slits

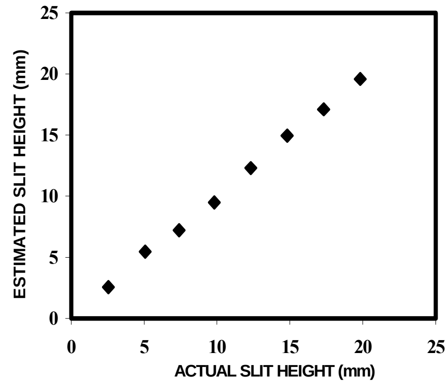


Figure - 6. Estimation of through thickness height for inclined slits

Table - 4

Aspect ratio for vertical slits based on			Aspect ratio for inclined slits based on		
Actual values	Estimated values	Error	Actual values	Estimated values	Error
0.0728	0.0778	+0.005	0.1024	0.0991	-0.0033
0.0963	0.0909	-0.0054	0.2028	0.2109	+0.0081
0.155	0.16	+0.019	0.3695	0.3531	-0.0164
0.241	0.238	-0.003	0.4915	0.4649	-0.0266
0.396	0.378	-0.018	0.4928	0.4929	+0.0001
0.598	0.617	+0.019	0.592	0.5991	-0.0071
0.666	0.6777	+0.0114	0.692	0.6865	-0.0055
1.502	1.527	+0.025	0.7928	0.7856	-0.0072
1.672	1.653	-0.019	-	-	-

$$\text{Aspect Ratio} = \frac{\text{Height of the crack}}{\text{Length of the crack}}$$

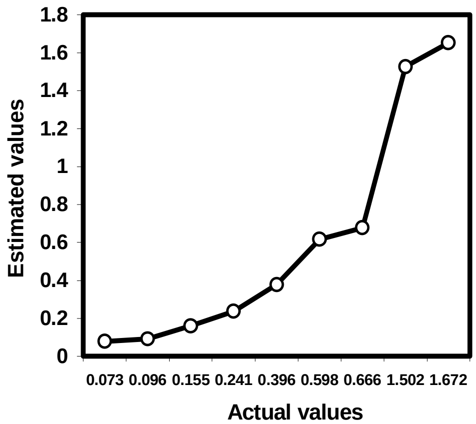


Figure - 7. Aspect ratio for vertical slits

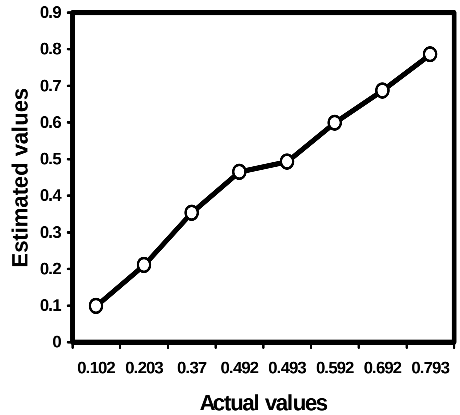
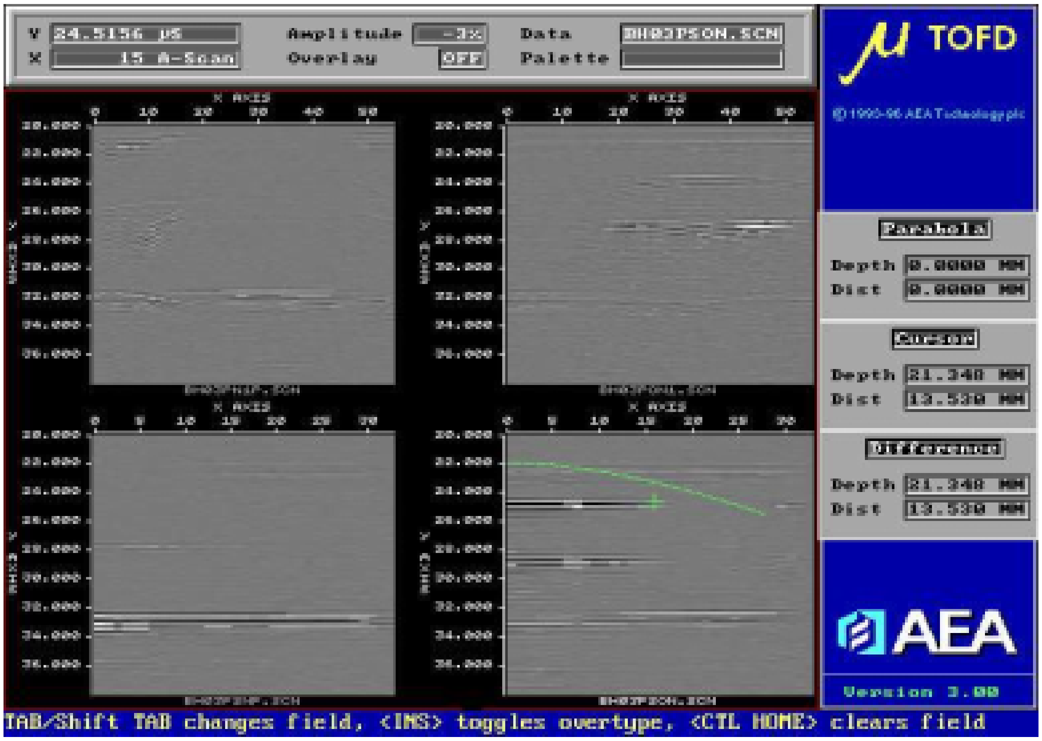


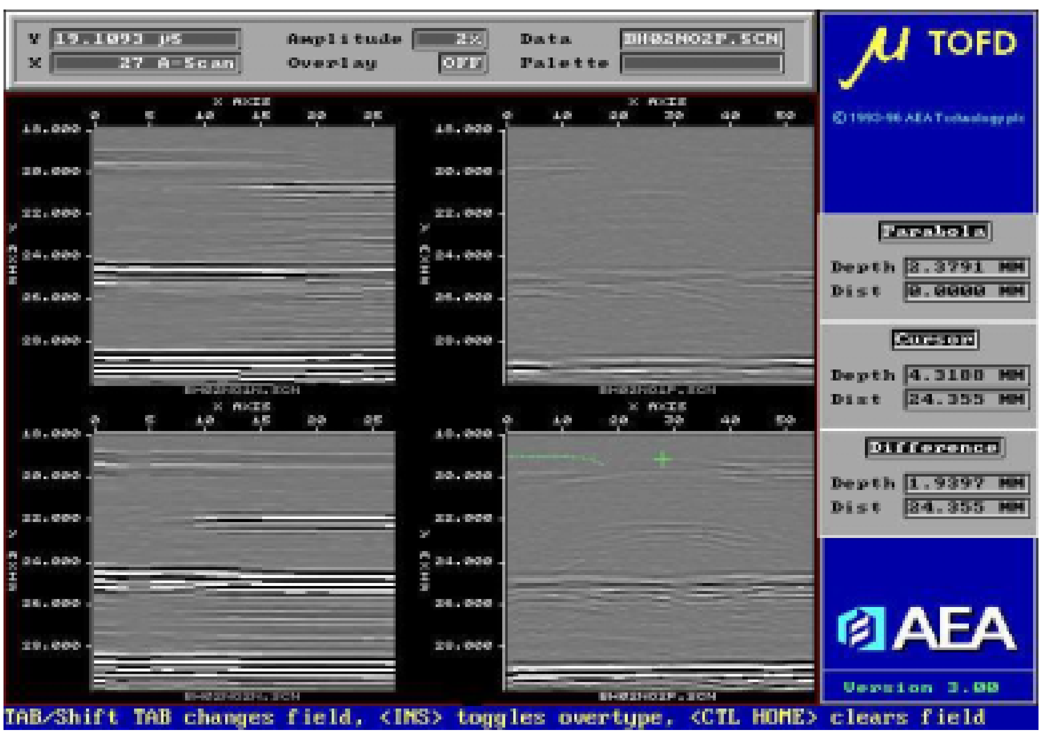
Figure - 8. Aspect ratio for inclined slits

Table – 5

	Mean error		SD		Sample details	
	Vertical slits	Inclined slits	Vertical slits	Inclined slits	Vertical slits	Inclined slits
Through thickness height	0.132mm	0.0542mm	0.155	0.238	9	8
Length extremities	0.357mm	0.285mm	0.376	0.379	6	4
Aspect ratio	0.00378	0.00724	0.00029	0.0004	9	8

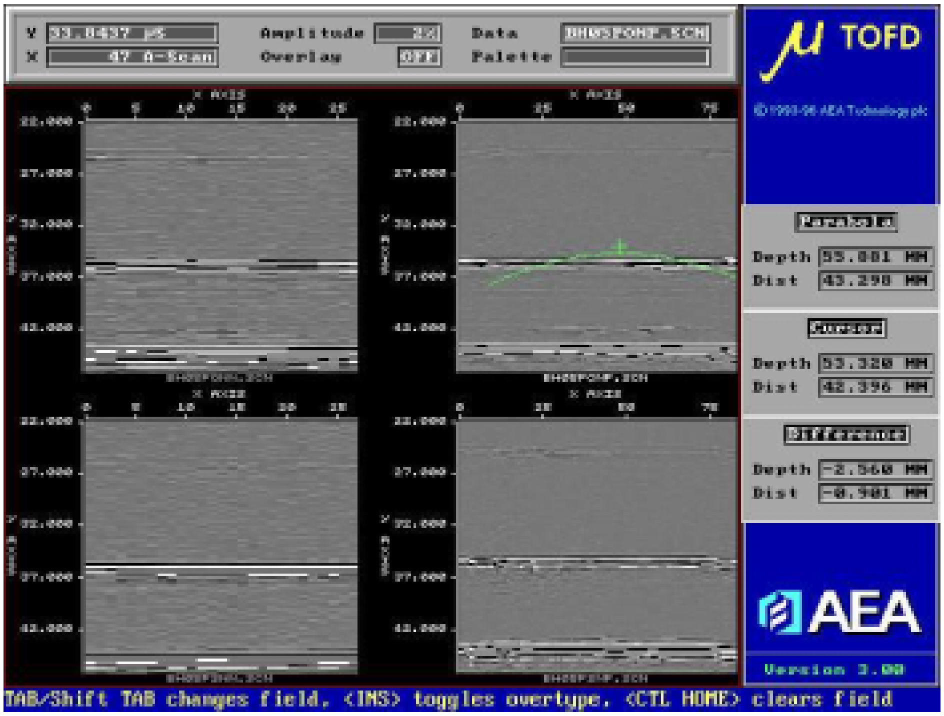


(a) Slit height of 1.82mm & length of 25mm

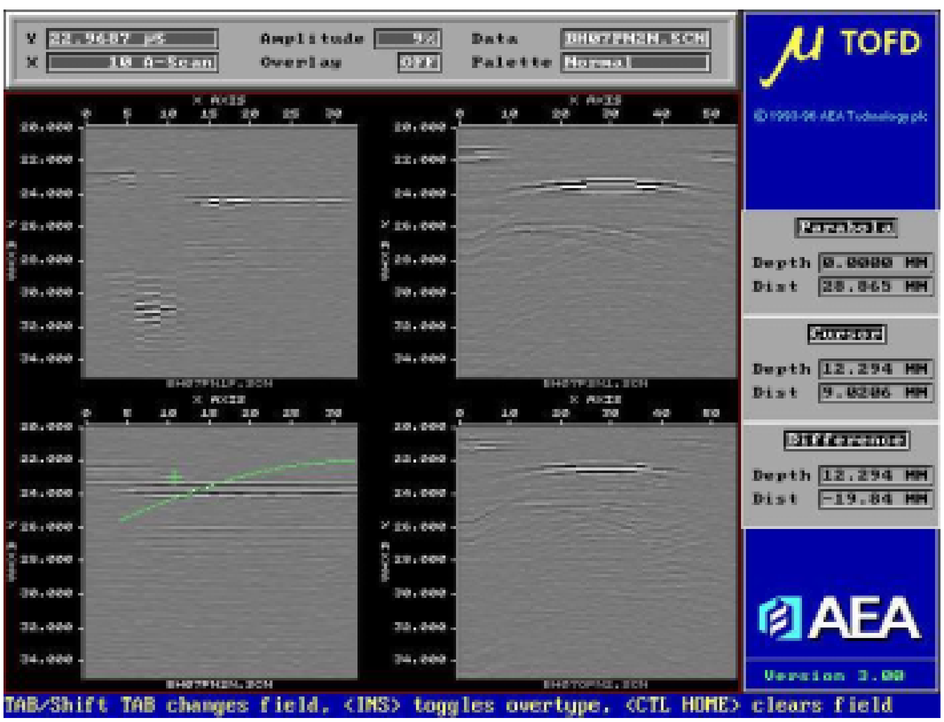


(b) Slit height of 30mm & length of 19.980mm

Figure - 9 TOFD images for vertical slits



(c) Slit height of 2.56mm & inclined at 15°



(d) Slit height of 12.32mm & inclined at 10°

Figure - 10 TOFD images for inclined slits

7.0 Results & Discussion

The experimental results have shown excellent correlation between the actual and estimated through thickness height and length of the simulated cracks (slits). In case of the vertical slits the mean error is found to be ±0.132 and the SD is 0.155 and in case of inclined slits the mean error is found to be 0.0542 and the SD is 0.238. As it can be seen from the results that the diffracted signal from the inclined slit (10° & 15°) is comparatively insensitive to angle and hence the diffraction is very good as a locator of defects [(15)]. This is because of the fact that the technique does not depend upon the amplitude of the signal. The TOFD method evaluates diffracted echoes, which are 20dB less than the reflected echoes (than a 3mm φ SDH). It must be noted that the diffracted waves have a different velocity than the reflected longitudinal waves [(16)]. It has been seen that both detection and sizing can be performed instantaneously from the same source data without any need to recalibrate and rescan using additional or alternate techniques. TOFD does not rely on a comparative assessment to quantify the significance of the detected defect. The proven level of accuracy attainable is found to be within ±0.1mm in terms of critical through wall extent and ±0.3 in terms of horizontal dimension and the angular disposition is resolved to within 3°. It has been observed that TOFD suffers from a near surface effect caused by its inherent lateral wave. Difficulty was experienced to size defects extending less than about 2mm depth. This is due to lateral wave, which obscures the tip-diffracted signals from the defects close to the surface and also due to the inherent lack of time resolution near the surface. With this technique it was possible to rapidly inspect large areas and thick section by linearly scanning very wide beam transducers at relatively very high speed and processing all high-resolution positional inspection data in effective real time [(7)].

Longitudinal waves were preferred over shear waves in order to reduce the ambiguity about sources of signals. The diffraction co-efficient for longitudinal waves varies with angles subtended, but there is only one narrow range of angle conditions of which the co-efficient is null. Using longitudinal waves the signal phase reliably distinguishes between defect top and bottom edges except that, if the angle sum is less than 76°, then the crack bottom signal phase is inverted. In longitudinal waves the lateral wave is used as a reliable timing reference [(17)].

It was also observed that the untreated TOFD B-scan image does not show a reconstruction of the defect, but only possible locations of special points of defects. The problem has been solved by a Synthetic Aperture Focusing Algorithm (SAFT) [(18)].

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