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TIME OF FLIGHT DIFFRACTION – AN ALTERNATIVE TO RADIOGRAPHY EXAMINATION OF THICK WALLED STAINLESS STEEL WELDMENTS

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ABSTRACT

Austenitic stainless steel is widely used in the nuclear industry as structural material because of the creep strength, corrosion resistance and very good high temperature fracture toughness. In the present experimental work, conventional radiography, pulse echo (manual and automated) and TOFD was used to evaluate austenitic stainless steel weld pads of 25 mm thick with defects such as lack of penetration, slag and porosity. Welding of these pads was carried out using shielded metal arc welding process. Double V configuration was used. Analysis of the results clearly indicates that TOFD has the advantage of faster scanning times and can be used for quantitative characterization (size and depth of defects) with accuracies better than $\pm$ 10%.

INTRODUCTION

Detection and quantification of discontinuities are very important especially in strategic and core sectors such as nuclear, petrochemical, and process industries. Conventional non-destructive testing (NDT) techniques such as radiographic testing (RT) and ultrasonic testing (UT) play a very crucial role during fabrication and in-service ensuring the safety, reliability and compliance to codal requirements. With the advent of imaging systems, UT is slowly replacing radiography for weld examination. Codes of practice such as ASME now permit UT in place of radiographic examination. Code case 2235 allows ultrasonic examination in place of radiographic examination while using ASME Section III and Section VIII Division 1 and Division 2 for Pressure Vessels with the minimum wall thickness from 1/2 ″ onwards.

While pulse echo ultrasonic techniques are well established, time-of-flight diffraction (TOFD) technique is a relatively new ultrasonic imaging method which is slowly gaining acceptance for thick walled weldments. This technique is based on the principle of measurement of time of flight of the diffracted echoes that are generated from the top and bottom tips of a defect or discontinuity when a longitudinal wave is incident on it [1-3]. The main advantages of TOFD compared to pulse echo UT and RT are:

(a) Rapid scanning is possible and weldments can be scanned in single pass making this technique more efficient and faster.
(b) Discontinuity size and depth can be very accurately determined. Since the technique is based on the detection of diffracted signals, it is not affected by the orientation of the discontinuity and angle of examination.
(c) Longitudinal angle beam being used by TOFD makes it possible to examine thick austenitic stainless steel weldments.
(d) Real time discontinuity monitoring is possible and the data can be stored for further reference and analysis.

Internationally, a number of studies have been undertaken [4-11] on the application of TOFD for detecting and sizing defects. The Dutch welding institute had undertaken a project in 1995 in which about 250 real defects were examined in specimens with thickness ranging from 6mm to 15mm [5]. This study revealed that compared to conventional techniques, TOFD is most effective technique that combined the highest probability if detection (~ 82.4%) and low false call rate (~11%). Presently, the technique is being widely applied for weldments with thickness in excess of 12.5 mm.

At the author's lab, a study was undertaken to compare the detectability of defects such as lack of penetration, porosity and slag in thick walled weldments by conventional techniques such as radiography, pulse echo UT and TOFD. Results clearly indicate that TOFD has the advantage of faster scanning and can be used for quantitative characterization (size and depth) of discontinuities with accuracies better than ± 10%.

EXPERIMENTAL DETAILS

Austenitic stainless steel (AISI 316L) double V butt welded joints of thickness 25 mm were used in this study. The details of the weld configuration are given in fig 1. A root gap of 2 mm and land of 2 mm was maintained. The bevel angle was 35±2°. The specimens were welded by shielded metal arc welding (SMAW) process, using standard welding procedures. The numbers of passes were 25. A total of 3 welded specimens were prepared. The defects - lack of penetration (LOP), slag inclusion and porosity were intentionally introduced in the specimens during the welding process. The face of the weld was ground flush to facilitate ultrasonic scanning using longitudinal angle probes by pulse echo technique. The specimens were subjected to radiography, ultrasonic pulse echo technique with manual and automatic scanning and TOFD.

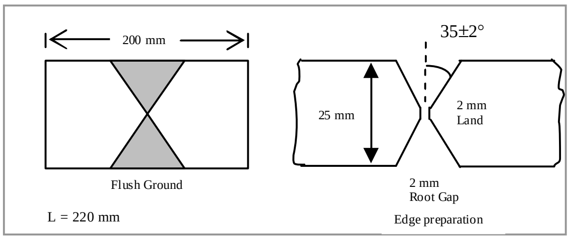


Figure 1: Details of the Weld Configuration

Radiography was carried out using a 200 kV X-ray source model Seifert 200 MF having a focal spot of 1.5 mm ×1.5 mm. Single wall single image technique was used. To minimize unsharpness, a source to focal distance (SFD) of 800 mm was used. The radiographic parameters are summarized in Table 1. The radiographs were digitized using UMAX Powerlook 3000 Scanner. Appropriate image processing techniques were adopted to enhance the edges of the defects for accurate dimensional measurements.

Table-1 Radiographic Parameters

X-ray Source	Seifert 200MF
Voltage	180 kV
Exposure	60 mA – mins.
SFD	800 mm
Film	Agfa D7
Technique	Single Wall Single Image (SWSI)
Image Quality Indicator	Plaque type
Processing	Manual
Sensitivity	2-2T
Radiographic Density in region of interest	2.0 – 2.5

Ultrasonic examination was carried out on the specimens using pulse echo manual and automated scanning and TOFD techniques. Standard grease was used as the couplant. For pulse echo technique, the equipment USD 10 of M/s Krautkramer, Germany with 45, 60 and 70 degree longitudinal angle beam transducer probes were used. The scanning was performed manually and using a automatic scanner normal to the weld axis. Automatic scanning was performed with Microscan Equipment of M/s AEA Technology, UK with μ-scan software with a raster length of 220 mm (specimen length) and 30 mm scan length, using an encoder attached to X-Y scanner.

For TOFD examination, the equipment used was MICROPLUS from AEA Technology, UK with TOFD software and 45, 60 and 70 degree longitudinal angle beam transducers of M/s Krautkramer, Germany. The scanning was encoded using an encoder along and normal to the weld axis.

RESULTS AND DISCUSSION

The digitized radiographic images were subjected to image processing and enhancement. Contrast stretching and edge enhancement through spatial filtering was adopted. Figs. 2-4 are the contrast stretched radiographic images. The lack of penetration (LOP), slag and clustered porosities (indicated by arrows) can be clearly seen. The length of the defects was estimated by profiling the defective area and using the full width at half maximum. Initial calibration was done using the images of the penetrameter hole and wire diameters. The depth of the defect was not estimated as it required multiple exposures (minimum two for double exposure parallax method).

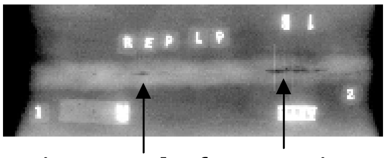


Fig 2 – Lack of Penetration

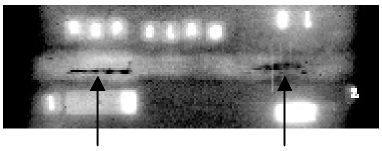


Fig 3 – Slag Inclusion

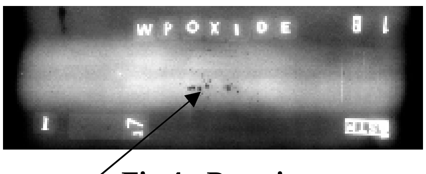
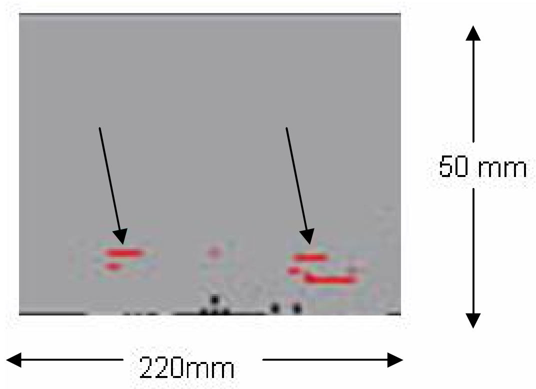


Fig 4 - Porosity

In the case of ultrasonic testing by pulse echo manual (PEM) scanning technique, the specimens were examined by manual scanning and the length and depth was noted. The length was arrived at by the conventional 12 dB drop method and the depth as indicated by the equipment based on the Distance Amplitude Correction curve was taken. Figures 5-6 are the images of the defects obtained by UT-pulse echo technique with automatic scanning (PEA) and the corresponding TOFD images. To estimate the length and depth of the discontinuity the images were taken with the reporting level of 50% and with required gate length. In the case of TOFD, the depth and length of the defects was obtained using the software provided by AEA based on the time of flight of the signals.



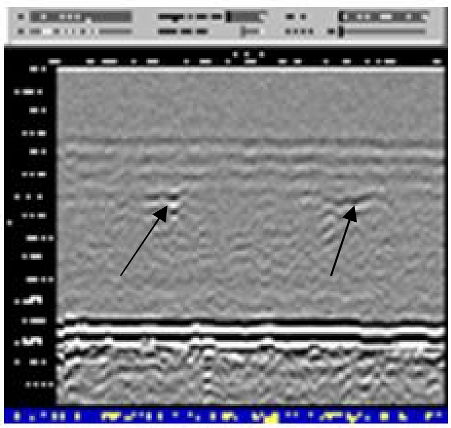


Fig. 5 - UT Pulse echo (top) and TOFD image of Lack of Penetration (bottom)

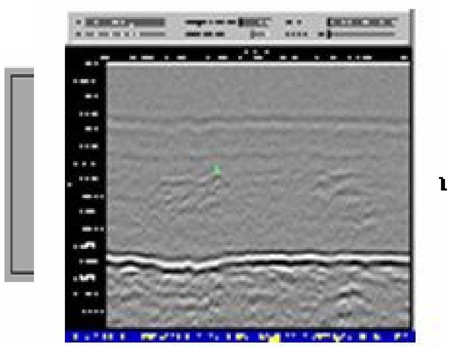


Fig. 6 – UT Pulse echo (top) and TOFD image (bottom) of slag

The length and depth calculated by the three methods and the actual sizes of the defects obtained through destructive measurements are summarized in Table 2. The percentage variation between the actual values and the values estimated by the various methods are summarized in Table – 3.

It can be observed from Table 3 that the variation in the actual size (length) and estimated size is minimum in the case of radiography varying between 1.45 % for LOP to 2.4% for porosities. This is quite understandable since precise measurements can be made from the radiographs.

In the case of ultrasonic methods, manual pulse echo presents the largest variation. This is attributed to vagaries in manual scanning and also the effects of beam divergence. Between automated pulse echo and TOFD, it can be clearly seen that TOFD is more accurate when sizing defects such as lack of penetration and slag. In the case of porosities, automated pulse echo appears much better with variation being as low as 2 % compared to TOFD in which the error is as high as 11%. This higher error can attribute to the fact that the diffracted signals from the porosity are weak due to the absence of sharp edges. In all the cases above, the accuracy of defect sizing can be improved upon through the use of appropriate image and signal processing techniques. A comparison of the total time taken for complete inspection of the weld indicates that radiography is highly time consuming while TOFD ranks the best with scanning times being approximately 1/10th to 1/20th, compared to automatic pulse echo technique.

Table 2– Length and Depth of Discontinuities and Porosity Area Arrived by NDE Methods

Discontinuity/ Exam method	LOP 1		LOP 2		Slag 1		Slag 2		Porosity		
	Length	Depth	Length	Depth	Length	Depth	Length	Depth	Length	Depth	Area (mm^2)
Actual	29.5	--	34.5	--	34.5	--	29.5	--	24.5	--	--
RT	30.0	--	35.0	--	35.0	--	30.0	--	25.0	--	120&70
PE Manual	35.0	10.6-12.6	45.0	13.1	40.0	10.4-11.8	35.0	11.8-13.2	30.0	8.1-10.76	140&80
PE Automatic	28.0	12.3	38.0	12.3	38.0	10.5	28.0	12.6	25.0	8.9-10.5	130&75
TOFD	29.0	12.76	38.0	12.76	37.0	10.12	29.0	13.31	22.0	9.0-9.9	125&75

Table – 3 Percentage Variations on Sizes of Discontinuities

Discontinuity/ Exam method	LOP 1	LOP 2	Slag 1	Slag 2	Porosity

RT	1.7%	1.45%	1.8%	1.7%	2.4%
PE Manual	18.6%	30.3%	12.7%	18.7%	22.5%
PE Automatic	- 5.1%	10.1%	10.1%	- 5.1%	2.0%
TOFD	- 1.7%	10.1%	7.3%	- 2.7%	- 11%

CONCLUSION

The advances in sensors, software and instrumentation has resulted in yet another technique – time of flight diffraction for NDE applications. The experimental work by the authors as well as international literature clearly indicates that TOFD compares well with the conventional techniques such as radiography and ultrasonics for defect detection in thick walled weldments. The results obtained by the authors through systematic experimentation on weld pads with defects is also a clear pointer to the capability of TOFD to detect and also accurately size the defects with very fast scanning times. TOFD could estimate the size of defects such as lack of penetration and slag with errors less than 7.5 % and scanning times about 1/10th to 1/20th compared to automated pulse echo. In the case of rounded indications the errors were found to be higher (~11%). However with the advances in the signal processing approaches it is possible to minimize these errors. The confidence generated by these investigations has resulted in TOFD replacing conventional radiography especially for weldments with wall thickness greater than 15 mm in the author's lab.

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REFERENCE

1. J.A. Ogilvy and J.A.G. Temple, Diffraction of elastic waves by cracks: application to time of flight inspection, Ultrasonics, November 1983, pp. 259 - 268.
2. F.A. Ravenscraft, K. Neuton and C.B. Scruby, Diffraction of ultrasound by Cracks: comparison of experiment with theory, Ultrasonics, January 1991, vol.28, pp. 29 -37.
3. J.P. Charles worth, J.A.G. Temple, Engg. Application of ultrasonic Time of flight diffraction, 2nd ed. Research Studies Press Ltd., 2001.
4. M.G. Silk, An evaluation of the performance of the TOFD techniques as a means of sizing flaws, with particular reference to flaws with curved profiles, Insight, vol. 38, No 4 April 1996, pp. 280-287.
5. J. Verkooijen, TOFD used to replace radiography, Insight Vol.37 No.6 June 1995 pp.433- 435.
6. Chris Gartside and John Hurst, Application of TOFD inspection techniques to fastness in power generating plant, Insight vol. 36 No 4 April 1994. pp. 215-217.
7. M. MacLay and J. Verkoojen, Time-of-flight diffraction technique for weld inspection, 13th international conference on NDE in the Nuclear and pressure Vessel Industries, pp. 125-129.
8. Mudge P.J. and A.C. Duncumb, NDT of steel bridges, Proceedings of the 20th Annual British Conference on NDT, September 1985, pp. 321-333.
9. C.A. Lany, J.M.A. Rebello, A. Saucer and J. Chartier, Surface crack sizing

related to the stress stayed by an ultrasonic time of flight technique, Insight Vol.40 No.6 June 1998, pp. 421-428.

10. M.G. Silk, The use of diffraction-based time of flight measurements to locate and size defects, Brit J NDT 1984, Vol 26, pp. 208-213.
11. M.G. Silk, Defect sizing using ultrasonic diffraction. Brit J NDT 1979, Vol. 21, pp. 12-15.