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ULTRASONIC STUDY FOR THE FLAW DETECTABILITY IN FERRITIC BUTT WELDS AT HIGH TEMPERATURES

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ABSTRACT

This paper describes the problems encountered during ultrasonic testing of welds at high temperatures, the overall assessment of sound propagation at high temperatures and an innovative technique to circumvent the problems using the conventional probes. In the absence of high temperature transducers an attempt has been made by the authors to examine the welds in the high temperature zone up to 300°C by using contact angle beam probes (less than 4MHz) and scanning from the region (beyond 5th Vee path) at room temperature. The experimental study involved embedment of natural defects like cracks, incomplete penetration, porosity etc., in the ferritic butt weld (16mm thickness) at predetermined locations. The comparative study was carried out between the responses obtained from the defects at ambient temperature and elevated temperatures. The analysis of the results have shown that the attenuation of ultrasound increases as the temperature at the weld zone increases. It can be seen from the results of the experiments that by making the attenuation corrections at elevated temperatures it is possible to inspect the welds below 300°C without substantial performance loss at test frequencies less than 4MHz.

1.0 Introduction

Ultrasonic testing is one of the powerful tools for condition monitoring and in service inspection of critical welds in thermal and nuclear power plants. Normally the testing is carried out at ambient temperatures during shut down. However there are number of occasions wherein the ultrasonic testing of the welds has to be performed at elevated temperatures or in areas where the temperature is not controlled [(1)]. The components under examination might be carrying fluid /steam at temperatures ranging from 50°C to 500°C. Unfortunately there are many problems associated with testing of welds at high temperatures. There are various factors that affect the ultrasonic test results at high temperatures. The temperature changes cause ultrasonic velocity changes, which in turn causes a change of beam angle there by improper location of the defects [(2, 3)]. The testing of welds at high temperatures requires highly specialised and costly transducer for continuous scanning, which are not easily available. An innovative method was adopted to restrict the weld zone at high temperature and testing from the cold zone. This permitted the use of conventional angle beam transducers.

2.0 The influence of ambient temperature on ultrasonic testing

2.1 Variation in ultrasonic velocity

Ultrasonic velocity in carbon or low alloy steel materials does not change significantly within the ambient temperature range from - 35°C to +60°C, although, it does decrease slightly with increase in temperature [2,5] as shown in Figure – 1 [4]. For most carbon alloy steels, the temperature co-efficient of ultrasonic velocity is approximately – 0.009 percent / °C. Velocity does vary with composition, method of fabrication and heat treatment. Table-1 [2] shows how velocity varies with temperature for typical alloy steels.

Table – 1. Ultrasonic velocity in steel sample

Temp.	Velocity Km/s	
°C (°F)	V_l	V_t
17(63)	5.790	3.240
27(81)	5.785	3.237
37(99)	5.779	3.233
47(117)	5.773	3.230
57(135)	5.767	3.226

Table – 2. Ultrasonic velocity in some angle - beam wedges

Temp.	Velocity Km/s		
°C (°F)	Wedge A	Wedge B	Wedge C
17(63)	2.78	2.76	2.69
27(81)	2.76	2.73	2.67
37(99)	2.74	2.70	2.65
47(117)	2.72	2.68	2.63
57(135)	2.69	2.65	2.62

The materials used for ultrasonic angle beam transducer wedges, such as Lucite and polystyrene exhibits a much greater rate of velocity change with temperature. A typical co-efficient is 0.08percent / °C, almost ten times the rate in steels. Table- 2 [2] shows longitudinal ultrasonic velocities measured in some typical wedges.

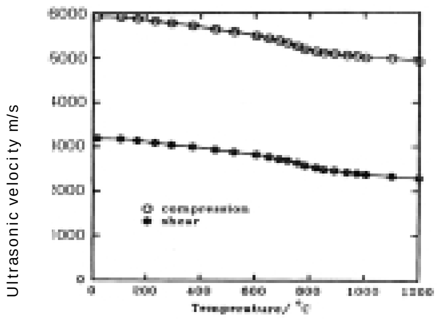


Figure -1 Ultrasonic compression & shear velocity of mild steel as a function of increasing temperature

2.2 Variation in beam angle

Temperature changes cause velocity changes, which in turn cause change of beam angle. The angle increases with increasing temperature as velocities in two materials (plastic and steel) becomes further apart. Large angles change more rapidly than small angles for a given change in the value of the sine of the angle. Therefore 70° probe change more per unit temperature change than 45° (5, 6). Table –3(2) shows some typical observed temperature – beam angle relationship. These changes must be considered along with other geometrical factors and testing variables to assess the location and sizing of flaws (7).

Table – 3. Typical temperature beam – angle relationship

Nominal angle at 20°C	Temperature coefficients [a]	
	Nominal [b]	Range Observed [c]
45±2	0.03/°C	0.03 – 0.05/°C
60±2	0.045/°C	0.04 – 0.08/°C
70±2.5	0.08/°C	0.08 – 0.12/°C

Where

[a] – The temperature coefficient expresses the change in angle, measured in degrees, per degrees celsius of temperature change.
[b] – Data provided by one manufacturer of transducers.
[c] – Range from an assortment of wedges from several suppliers.

2.3 Elastic moduli and temperature

Velocity and elastic moduli are functions of temperature. The temperature dependence is important because elastic moduli are related to interatomic forces. Elastic constants are related to interatomic forces. Elastic moduli indicate maximum attainable strengths(8,9, 10). The longitudinal and shear moduli usually vary linearly with temperature.

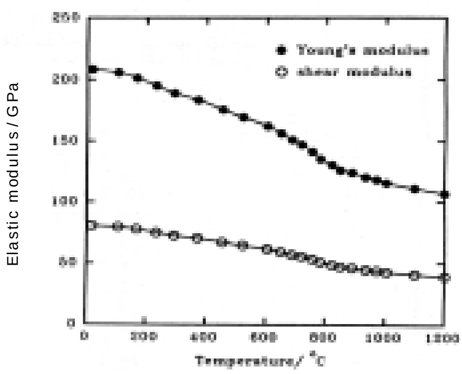


Figure - 2 Young's modulus & shear modulus of mild steel as a function of increasing temp. as derived from ultrasonic data of Fig.1

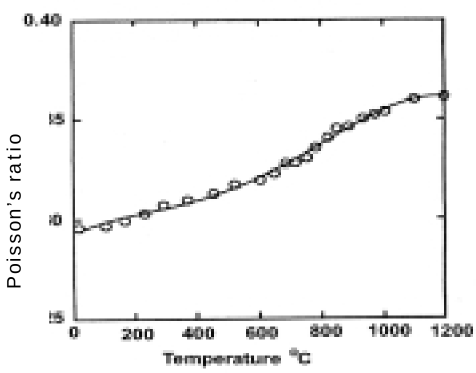


Figure - 3 Poisson's Ratio of mild steel as a function of temperature

Young's modulus and shear modulus of mild steel is a function of temperature as derived from ultrasonic data as shown in Figure – 2 [4]. From the Figure - 2, it can be seen that as the temperature is raised, young's modulus decrease monotonically to 54% of its room temperature values for mild steel. Figure – 3[4] shows Poisson's ratio of mild steel as a function of temperature as derived from the ultrasonic data. Poisson's ratio rises with temperature from 0.296 to 0.356 in mild steel [4].

3.0 EXPERIMENTAL WORK

The experimental study involved the embedment of natural defects like cracks, incomplete penetration and porosity in the ferritic butt weld at predetermined locations and the ultrasonic flaw detectability study at elevated temperature. (Refer Table – 4 and Figure– 4a & 4b). The weld zone was elevated to various temperatures by using induction-heating coils (Kanthal wire) and the temperature measurements were accurately made by using the thermocouples (Chromel Alumel) with an accuracy of ±0.1°C. To control the heat transfer loss, asbestos sheets were wrapped around the induction coil and the job. In the absence of high temperature transducers, the weld scanning was done from the cold zone (beyond 5th Vee path) using the contact angle beam probe MWB 45°- 4 MHz and the digital ultrasonic flaw detector USN 52R. The testing was done with a sensitivity of 1.5mm CRR. The scanning zone was cooled by continuous flow of water during testing without affecting the weld zone temperatures. The signal amplitude, beam path, the projected distances, location and depth were recorded for each defect at different temperatures ranging form 35°C to 300°C. The experimental observations are shown in the Table 5a, 5b, 6a & 6b.

3.1 SPECIMEN DETAILS

Specimen – 1

Material: Carbon steel
Plate size: 16mm x 100mm x 600mm
Welding Process: MMAW
Edge Preparation: Single Vee

Specimen – 2

Material: Carbon steel
Plate size: 16mm x 100mm x 600mm
Welding Process: MMAW
Edge Preparation: Double Vee

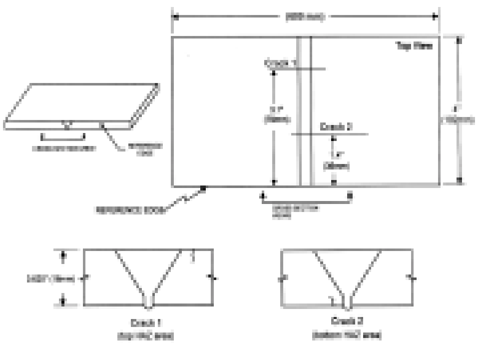


Figure – 4a Flaw locations Specimen – 1

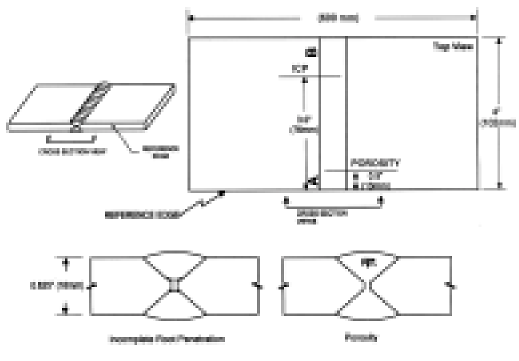


Figure – 4b Flaw locations Specimen – 2

Table – 4. Actual Flaw Locations

Discontinuity Description	Start of flaw to Ref.(mm)	Total flaw length (mm)	Flaw height (mm)	Flaw depth below surface (mm)
Specimen - 1				
Crack at top HAZ area of the weld	36	15	3.8	Surface Breaking
Crack at bottom HAZ area of the weld	79	8	3.8	Surface Breaking
Specimen - 2				
Incomplete Root Penetration	76	13	3.8	8
Porosity	13	18	3.8	2.5

Table – 5a. Flaw detection in specimen – 1 at elevated temperature

Responses from crack -1					
Temperature°C	Gain (dB) signal 50% of FSH	Observed Beam Path (mm)	Observed projected distance (mm)	Observed depth below surface (mm)	Location (Start of flaw to Ref.) mm
Room temp 35	48.0 48.9	228.8 229.4	150.0 150.2	3.8 3.8	38 38
60	49.6	229.4	150.2	3.8	38
65	49.7	230.1	150.7	3.3	38
90	49.8	230.1	150.7	3.3	39
100	50.0	229.6	150.4	3.6	39
110	50.4	229.8	150.5	3.5	39
125	50.6	230.9	151.2	2.8	39
135	50.9	230.7	151.1	2.9	39
145	51.1	230.4	150.9	3.1	39
165	52.3	231.5	151.7	2.3	40
200	52.6	232.8	152.6	1.4	40

Table – 5b. Flaw detection in specimen – 1 at elevated temperature

Responses from crack - 2					
Temperature°C	Gain (dB) signal 50% of FSH)	Observed Beam Path (mm)	Observed projected distance (mm)	Observed depth below surface (mm)	Location (Start of flaw to Ref.) mm
Room temp	48.2	213.5	139.0	1.0	80
40	48.4	214.8	139.9	1.9	80
50	49.4	214.8	139.9	1.9	80
60	49.4	214.8	139.9	1.9	80
90	49.4	215.2	140.2	2.2	80
97	49.7	216.3	140.9	2.9	81
110	50.0	214.7	139.8	1.8	81
140	50.3	215.4	140.3	2.3	81
150	50.7	214.8	139.9	1.9	82
160	50.8	214.9	140.0	2.0	82
200	51.0	214.6	139.8	1.8	82

Figure – 5 Photograph showing the UT at high temperature under progress

Table – 6a. Flaw detection in specimen – 2 at elevated temperature

Responses from Incomplete Penetration					
Temperature°C	Gain (dB) signal 50% of FSH)	Observed Beam Path (mm)	Observed projected distance (mm)	Observed depth below surface (mm)	Location (Start of flaw to Ref.) mm
Room temp	58.9	243.0	159.8	8.3	77
40	59.0	243.0	159.8	8.2	78
45	59.1	242.8	159.7	8.3	78
55	59.5	242.9	159.8	8.2	78
65	59.9	242.6	159.6	8.5	78
80	60.0	242.8	159.7	8.3	78
90	60.3	242.9	159.7	8.3	79
120	60.4	242.8	159.7	8.3	80
130	61.0	243.3	160.1	8.0	80
140	61.9	244.4	160.8	7.2	80
155	62.0	244.7	161.1	7.0	81
185	62.4	242.4	159.4	8.6	81
190	62.8	242.9	159.7	8.3	81
220	63.0	243.0	159.8	8.2	82
245	64.8	242.8	159.7	8.3	82
310	65.1	242.9	159.7	8.3	82

Table – 6b. Flaw detection in specimen – 2 at elevated temperature

Responses from Porosity					
Temperature°C	Gain (dB) signal 50% of FSH	Observed Beam Path (mm)	Observed projected distance (mm)	Observed depth below surface (mm)	Location (Start of flaw to Ref.) mm
Room temp	61.7	245.3	161.5	2.5	14
40 75	62.6 63.2	246.5 257.5	162.3 170.1	5.7 2.1	15 15
95	63.4	246.1	162.0	6.0	15
135	63.8	245.4	161.6	6.5	16
165	64.0	245.4	161.6	6.5	16
180	65.0	246.9	162.5	5.5	16
190	65.1	246.5	162.3	5.7	16
195	65.9	248.7	163.8	4.2	16
290	67.5	258.3	170.6	2.6	16
310	67.5	258.5	170.8	2.8	17

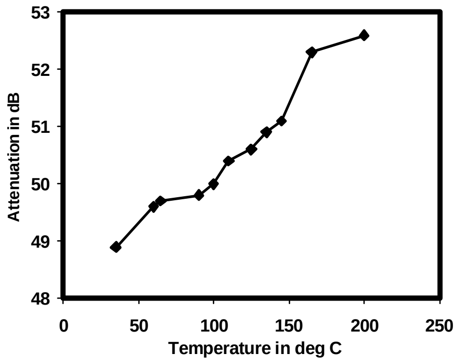


Figure - 6(a). Effect of temperature on detection of crack in specimen-1 (Top HAZ Area)

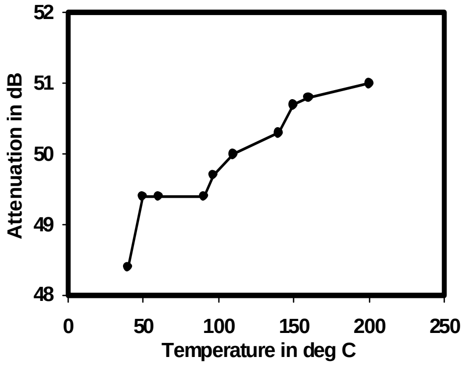


Figure - 6(b). Effect of temperature on detection of crack in specimen-1 (Bottom HAZ Area)

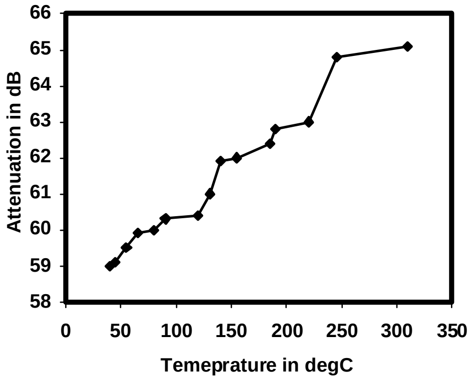


Figure - 7(a). Effect of temperature on detection of crack in specimen- 2 (ICP)

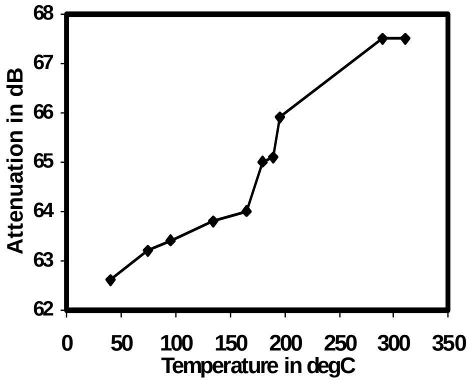
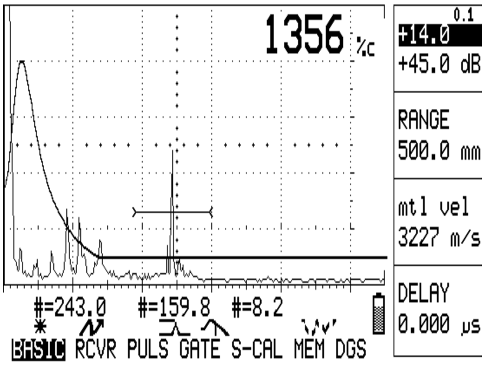
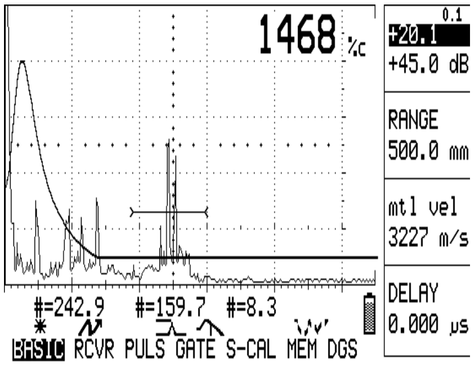


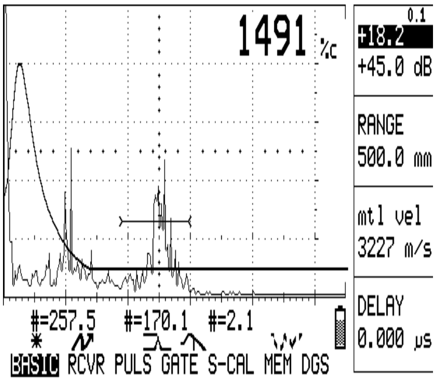
Figure - 7(b). Effect of temperature on detection of crack in specimen- 2 (Porosity)



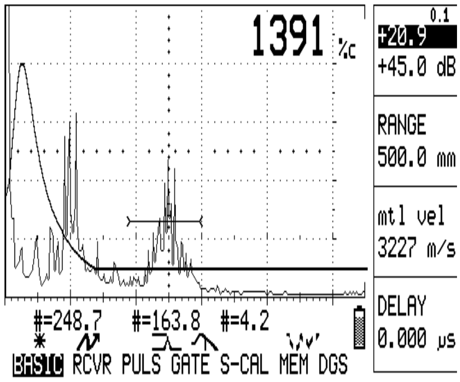
(a) A-Scan presentation of ICP at 40°C



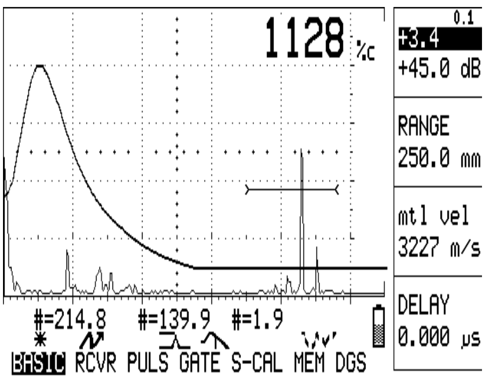
(b) A-Scan presentation of ICP at 310°C



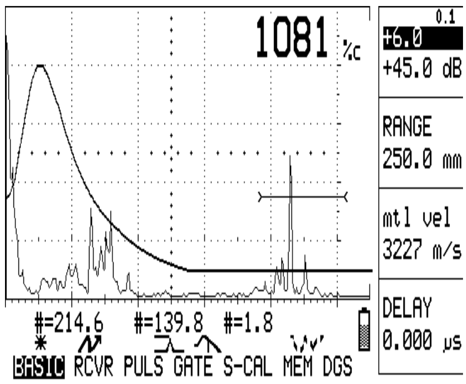
(c) A-Scan presentation of porosity at 75°C



(d) A-Scan presentation of porosity at 195°C



(e) A-Scan presentation of Crack at 40°C



(f) A-Scan presentation of Crack at 200°C

Figure – 8 Actual ultrasonic signals for defects in welds at different temperatures

4.0 SUMMARY & CONCLUSION

The analysis of the experimental data reveals the following:

- By making the attenuation corrections at elevated temperatures it is possible to inspect the welds below 300°C without substantial performance loss at test frequencies less than 4MHz.

- The attenuation of ultrasound increases as the temperature at the weld zone increases as shown in Figures 6A, 6B, 7A & 7B.

- There is a variation of maximum 1.5dB for the response from the flaws in the region of 100°C whereas above 200°C there is a significant variation in signal amplitude ranging from 3dB to 6dB compared to the amplitudes from the flaws at room temperatures.

- The signal amplitude at elevated temperatures also varied for different defects. (3dB for cracks and 5dB for porosity & 6dB for incomplete penetration). Refer Figure- 8.

- There is insignificant change in the location of the flaw while testing at elevated temperatures, in contrast to the published literature [2]. This is due to the reason that the transducer is in contact with the cold zone of the job while the weld under examination is at elevated temperatures. The ultrasound has to pass through only a small hot zone before interacting with the defect.

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