Monitor the circumferential welds of Multi-layer Thick-wall Pressure Vessels Serving at Elevated Temperature by Ultrasonic Testing

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Abstract

Through a series of researches and analyses the feasibility of ultrasonic inspection at high temperature, After some experimentation was carried at laboratory, It was applied on the cyclic welding seam of the multi-layer and thick-wall pressure vessel by using special high temperature probe & couples, And the high performance UT detector and the tip diffraction technology was recommended. Carry one's point of the ultrasonic monitor at high temperature of that equipment in service.

Keywords: Multi-layer and Thick-wall P.V.  In service  High Temperature  Ultrasonic Monitoring

1. Foreword

Urea reactor, a kind of multi-layer and thick walled vessel, is the key equipment in producing urea. In process of service, serious flaws, such as corrosive perforation and cracks, were respectively found in bottom-head and along the entire inside wall of cover-head to first shell joint due to fabrication and running operation. Serious cracks were basically removed after normal ultrasonic inspection and reparation.

We inspected all ten circumferential welds of this equipment using tip-diffraction technique so as to know the exact flaw status, many serious flaws were detected in bottom-head to shell (the 11th shell) joint (joint B) as listed in reference documentation (No.3). With the purpose of verifying the accuracy of ultrasonic inspection results, six checking windows were made on the inside wall (by removing a stainless surfacing by a size of 260 by 150 to make the steel layer
appear) and apparent indications of crack were observed, as shown in Fig 1 and Fig 2, when penetrant examination was performed inside these windows. Meanwhile, tip-diffraction technique was performed again on the outside wall corresponding to the checking window to measure the height of crack so that we can estimate the orientation of maximum size of flaw-itself in joint and provide reliable data for reparation.

On the basis of calculation and analysis by CVDA and at the premise of safe-running, flaws with height beyond limit were determined to be thoroughly removed and locally existing subcritical flaws were suggested to be remained under monitoring.

![Fig1: Crack indication inside window No.1](image1.jpg) ![Fig 2: Crack indication inside window No.4](image2.jpg)

It is necessary to perform high-temperature ultrasonic monitoring for both long period safe-running and the increase of production. High temperature ultrasonic monitoring was applied to monitor serious flaws in joint B of this Urea reactor after feasibility analysis, satisfactory test results obtained, using powerful double crystal longitudinal wave probe used for high temperature, special-made transverse wave probe (with refraction-angle of 45 degree and 63.4 degree) and couplant suitable for high temperature, big screen type detector and refitted constant temperature drier. This implementation provided CVDA with reliable data.

2. General situation of Urea reactor

2.1 Structure

This Urea reactor, 2.8 meters in radius 35 meters in height and consisting of eleven shells and two semispherical heads as shown in Fig 3, was fabricated by a foreign company in Jun 1976. Each shell is made of three shrinkage-fit layers (MnNiV steel) with liner against urea corrosion, stainless steel 316L 8mm in thickness. Semispherical head is forged and its material is A52C. On its inside wall is surfacing of material 21/17E 12mm in thickness.

2.2 Equipment parameters
Designing pressure: 15.59 MPa
Designing temperature: 193°C
Operating pressure: 13.53 ~ 13.83 MPa
Operating temperature: 183°C
Capacity: 195 m³
Joint coefficient: 1.0
Medium: urea, water, ammonia, CO₂

2.3 Structural trait of joint

Structure of head-to-shell joints (circumferential weld A, B) is shown in Fig 4: material on head-side is forge-curved and on its bottom is surfacing of material 21/17E 12mm in thickness,
shell is made of three shrinkage-fit steel layers. The first layer of shell has an angle of 18 degree and a length of 80mm welded to fusion zone and the second layer (see welded portion in Fig 4)

Structure of shell-to-shell joint is shown in Fig 5: on both sides of the joint are three shrinkage-fit steel layers with liner of stainless steel 316L 8mm in thickness which are welded to main joint to be integral.

On the bottom of all above mentioned structures there is a stainless steel transition layer with thickness of 12mm.

3. Feasibility analysis of ultrasonic inspection at high temperature

For ultrasonic inspection at high temperature, probe and inspection method are the biggest problems.

3.1 Limitations of normal probe

Generally, normal probe is designed to be used at temperature range of 10° to 60°. When it is used for surface temperature over 150°, the contact time is required to be extremely short because on one hand the acoustic characteristic will change with temperature and on the other hand the probe wedge will expand and get damaged at high temperature, so normal temperature probe can not be used for high temperature in which case high temperature probe must be selected.

Experimental results show: acoustic velocity in steel does not vary much. The refraction angle change little tested with calibration block CSK-IA when temperature raises from 20° to 65°.

However, refraction angle will change after the temperature over 65°: this variation has direct relationship with temperature, contact time between probe and component at high temperature, and coupling layer status. Given certain coupling layer and certain temperature, refraction angle will apparently increases when the contact time extends.

Why does refraction angle change with temperature? According to the equation:

$$\frac{\sin \alpha}{\sin \beta} = \frac{Cd}{Cst} \text{ or } \beta = \arcsin\left(\frac{\sin \alpha \cdot Cst}{Cd}\right)$$

In the equation: $\alpha$ — incidence angle; $\beta$ — refraction angle in steel

$Cd$: acoustic velocity in wedge of probe (m/s)

$Cst$: velocity of transverse wave in steel (m/s)

$Cst$ changes very little , $Cd$ decreases with the increase of temperature.

Temperature of wedge is not equal. If it is divided into three layers as shown in Fig 6, the temperature of each layer will be $T1 > T2 > T3$. Acoustic beam launched by piezoelectric is curved inside wedge which causes incidence point changed: incidence angle increase and refraction angle increase subsequently.
For a certain objector, there is a retrocession of its echo on sweep line

![Image 1](image1.png)  ![Image 2](image2.png)

**Fig 6: Orientation variation of acoustic beam at high temperature**

**Fig 7: DAC curves obtained at room temperature and high temperature**

### 3.2 Trial-produce of probe used for high temperature

Selection of wedge material shall be taken into consideration as a main issue in producing probe used for high temperature. The selected material shall have the qualities of little variation in acoustic beam direction, incidence point, incidence angle, flexibility and plasticity which could avoid damage due to thermo-expansion in the case of temperature increasing and contact time extending.

We entrust famous domestic manufacturer to produce following specified probes allowed to be used at maximum temperature of 250°C:

- Transverse wave probe with refraction angle of 45, 63.4 degree i.e. SRIM2.0L13×13 K1, SRIM2.0L13×13 K2
- Double crystal longitudinal wave probe with big diameter and focusing in a long cylinder

### 3.3 Couplant used for high temperature

Couplant is also a major consideration for ultrasonic monitoring at high temperature. As common couplant such as glycerin and mechanical oil which will provide bad coupling due to increase of fluidity and decrease of acoustic impedance at high temperature, naturally, couplant suitable for high temperature, such as silicon oil and coupling ointment, are determined to be used to overcome the shortcoming of variation of acoustic impedance due to temperature. For instance, couplant ZGT50472, manufactured by KK Company of German used at temperature range of -10°C to 250°C, has the same acoustic impedance at high temperature as the one of glycerin at room temperature.

### 3.4 Operation duration

Operation duration is also a factor which causes echo figure changed and inaccurate locating, so controlling of contact time within 3 to 5 seconds shall be strictly followed. This controlling will make it comparable with comparison curve and can be realized for monitoring designated point.

To sum up, it is practical to perform ultrasonic monitoring at high temperature for designated flaws using suitable probe, couplant, and strict controlling of contact time.

### 4. Inspection method and performance parameters
4.1 Transverse Wave Method

In laboratory, distance amplitude curves are established by following steps, using ultrasonic detector USM3S, probe SKIM2.0L13×13K, couplant ZGT.

Put CSKIIIA block inside refitted drier and heat it to 180°C. Keep the block at constant temperature of 180°C and make distance amplitude curve (for high temperature). Cool the block to room temperature and make another DAC (for room temperature) as shown in Fig 7.

On job site, using detector USM3S, probe SRIM2.0L12×13K1, relevant DAC corresponding to different temperature to inspect window No.1 (area of B4-5), No.4 (area of B20-21) of joint B where contains the most serious flaws for rechecking at room temperature and monitoring at high temperature respectively. Results are listed in table 1-1, 1-2.

Table 1-1: Testing results of flaws inside window No.1, 4 of joint B using transverse wave (at room temperature) USM3S + SRIM2.0L13×13K1 (Compensation of 4dB)

<table>
<thead>
<tr>
<th>Ultrasonic inspection at room temperature</th>
<th>Depth (mm)</th>
<th>Amplitude (dB)</th>
<th>Length (mm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window No.1</td>
<td>76-80</td>
<td>SL+12dB</td>
<td>140</td>
<td>Echo shown in Fig 12</td>
</tr>
<tr>
<td>Window No.4</td>
<td>78-82</td>
<td>SL+8dB</td>
<td>110</td>
<td></td>
</tr>
</tbody>
</table>

Table 1-2: Monitoring results of flaws inside window No.1, 4 of joint B (at high temperature) USM3S + SRIM2.0L13×13K1 (compensation of 4dB)

<table>
<thead>
<tr>
<th>Ultrasonic inspection at high temperature</th>
<th>A point</th>
<th>H point</th>
<th>B point</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window No.1</td>
<td>Depth</td>
<td>Amplitude</td>
<td>Depth</td>
<td>Amplitude</td>
</tr>
<tr>
<td>After repair</td>
<td>78</td>
<td>SL+7</td>
<td>76-81</td>
<td>SL+14</td>
</tr>
<tr>
<td>One year later</td>
<td>79</td>
<td>SL+8</td>
<td>75-81</td>
<td>SL+13</td>
</tr>
<tr>
<td>Window No.4</td>
<td>Depth</td>
<td>Amplitude</td>
<td>Depth</td>
<td>Amplitude</td>
</tr>
<tr>
<td>After repair</td>
<td>81</td>
<td>SL+9</td>
<td>79-82</td>
<td>SL+10</td>
</tr>
<tr>
<td>One year later</td>
<td>80</td>
<td>SL+3</td>
<td>78-82</td>
<td>SL+12</td>
</tr>
</tbody>
</table>

4.2 Longitudinal Wave Method

In laboratory, using double crystal longitudinal wave probe to produce DAC curves at different temperature with fatigue crack block (as shown in Fig 8) which is heated inside constant temperature drier to required step temperature from 30°C to 180°C and find the relationships between scanning, sensitivity and temperature. The results in table-2 indicate that there is a retrocession of echo on sweep line and decrease of sensitivity when temperature increases.

Table-2: Relations table between sensitivity, scanning ad temperature

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>30°C</th>
<th>90°C</th>
<th>120°C</th>
<th>150°C</th>
<th>180°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>5.75/70</td>
<td>5.80/72</td>
<td>5.80/74</td>
<td>5.80/76</td>
<td>5.80/78</td>
</tr>
<tr>
<td>61</td>
<td>6.10/77</td>
<td>6.15/76</td>
<td>6.20/76</td>
<td>6.20/78</td>
<td>6.25/84</td>
</tr>
<tr>
<td>71</td>
<td>6.55/80</td>
<td>6.55/78</td>
<td>6.60/78</td>
<td>6.60/77</td>
<td>6.65/82</td>
</tr>
<tr>
<td>81.5</td>
<td>6.80/80</td>
<td>6.80/82</td>
<td>6.80/82</td>
<td>6.90/80</td>
<td>7.00/82</td>
</tr>
<tr>
<td>91</td>
<td>7.20/76</td>
<td>7.30/76</td>
<td>7.40/80</td>
<td>7.40/80</td>
<td>7.40/80</td>
</tr>
<tr>
<td>101</td>
<td>7.60/74</td>
<td>7.70/76</td>
<td>7.75/74</td>
<td>7.80/78</td>
<td>7.80/78</td>
</tr>
</tbody>
</table>
In Period of examine & repair, windows No.1, No.4 were rechecked, using double crystal longitudinal wave probe (type: SIUI2.0L (7×18)×2TR) and method referencing to standard, Recommending Ultrasonic Inspection Method for Circumferential weld of multi layer vessels in service, inspection results were taken as comparison base for ultrasonic monitoring at high temperature.

After repair and one year later, ultrasonic monitoring at high temperature was applied for designated points inside windows No.1 and No.4 while equipment was running. Monitoring results are listed in table 3-1, 3-2.

Table 3-1: Longitudinal wave monitoring results of flaws inside window No 1, 4 of joint B (at room temperature) USM3S + SIUI2.0L(7×8)×2

<table>
<thead>
<tr>
<th>Ultrasonic inspection at room temperature</th>
<th>Sweep readings / depth</th>
<th>Amplitude (dB)</th>
<th>Length (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window No1*#</td>
<td>6.80/80</td>
<td>64</td>
<td>150</td>
<td>Echo shown in Fig 13</td>
</tr>
<tr>
<td>Window No 4*#</td>
<td>6.60/76</td>
<td>66</td>
<td>105</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-2: Longitudinal wave monitoring results of flaws inside window No 1, 4 of joint B (at high temperature) USM3S + SIUI2.0L(7×8)×2

<table>
<thead>
<tr>
<th>Ultrasonic inspection at high temperature</th>
<th>Sweep readings / depth</th>
<th>Amplitude (dB)</th>
<th>Length (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window No.1*#</td>
<td>After repair</td>
<td>6.90/79</td>
<td>68</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>One year later</td>
<td>6.95/80</td>
<td>66</td>
<td>148</td>
</tr>
<tr>
<td>Window No.4*#</td>
<td>After repair</td>
<td>6.80/77</td>
<td>70</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>One year later</td>
<td>6.75/76</td>
<td>68</td>
<td>105</td>
</tr>
</tbody>
</table>

Fig 8: Fatigue crack block

Fig 9: Depth-grid curve of fatigue crack

Fig 10: Transverse wave echo of flaws inside

Fig 11: Longitudinal wave echo of flaws inside
5. Discussion

5.1. It is difficult for root flaws of Urea reactor to be detected due to the intervention of interface echo from the stainless steel surfacing.

5.2. It is specified in this article that sweep distance readings of flaw shall be obtained when the amplitude of flaw echo reaches sixty percent of full screen because the readings will change with the variation of amplitude.

5.3. When high temperature type probe is used for ultrasonic monitoring at high temperature, reduction of sensitivity, increase of refraction angle, retrocession of echo on sweep line will happen.

5.4. This method is complicated and highly-demanded compared with normal method, especially the issue of contact time which must be controlled within three to five seconds will make it not practical for ultrasonic inspection work in large quantity.

6. Conclusion

I It is practical to realize ultrasonic monitoring for designated flaws at high temperature using special-made probe used for high temperature, ultrasonic detector with large screen and high resolution, and couplant suitable for high temperature.

II There is no deviation of depth readings of designated linear flaws observed for maximum echo with probe, high temperature type with refraction angle of 45 and 63.4 degree, positioned on designated location on head side of joint B; There is no abnormality in orientation of depth of designated flaws observed using tip-diffraction technique with probe, double crystal longitudinal wave probe used for high temperature, positioned on designated location

III Several results obtained through ultrasonic monitoring at high temperature indicate that there is no tendency of development of all monitored linear flaws. These results play important role to guarantee the safe-running of equipment.

IV It is a valuable reference for ultrasonic monitoring for thick walled equipments in service with manufactured or fabricated flaws and running at high temperature in a long period.

Reference documentation


请随稿提供第一作者信息【姓名，出生年，性别，职称(或学历学位)，专业方向】及通讯地址、邮编、手机(电话)及电子邮箱。

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