ULTRASONIC DETECTION OF PLASTIC DEFORMATION

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Abstract

Piping under critical internal pressure reaches the limit state (yield strength) first at the internal surface, propagating towards the outer surface. This process happens from inside out, thus it is difficult to monitor in its early stages. Some ultrasonic properties are sensitive to change of material properties induced by internal stress and strain. The article discusses possible applications of ultrasonic testing to detect such plasticized areas on pressure equipment piping.

Keywords: ultrasonic testing, piping, plastic deformation, plastic strain

1. Introduction

Plastic collapse of pressure equipment piping under high pressure, or combination of pressure and high temperatures, is a common phenomena in power industry. If piping is subject to critical level of internal pressure, it reaches the plastic state first on the internal surface, from where it propagates towards the outer surface. The collapse usually occurs before the plastic deformation reaches the outer surface. In the region of highest applied circumferential stress voids and microcracks are formed. Their coalescence eventually leads to a rupture of the piping along the main piping axis.

This article is proposing a non-destructive UT technique measurement of longitudinal to transversal waves velocity ratio to detect plasticity, both induced by pressure or combination of pressure and high temperature. The experiment is performed on a part of collapsed membrane wall due to creep, extracted from in-service combustion chamber. Results are compared with hardness HV.

2. Ultrasonic waves velocities

The velocities of longitudinal \( (c_L) \) and transversal \( (c_T) \) ultrasonic waves are dependent on the stress-strain conditions of the material. One of the possible notions can be expressed as follows:

\[
\begin{align*}
  c_L &= \frac{E}{\sqrt{\rho (1 + \nu)(1 - 2\nu)}} \\
  c_T &= \frac{G}{\sqrt{\rho}} = \frac{E}{\sqrt{\rho} 2(1 + \nu)}
\end{align*}
\]

where \( E \) and \( G \) are commonly referred as Young and Shear modulus and \( \nu \) is the Poisson’s ratio.

Acousto-elastic and acousto-plastic effects are responding to stress in elastically deformed body and to residual stresses created by macroscopic deformation. Since most residual stresses are induced by plastic strain, acoustic measurements of residual stresses are suitable candidate for the proposed application. It is well-known that velocity of the longitudinal
ultrasonic waves $c_L$ increases with applied load in elastic region while the velocity of transversal waves polarized either parallel or perpendicular to the load decreases. Team from Det Norske Veritas [1] experimentally confirmed, that the increase of velocity of the longitudinal waves is limited and when it reaches a critical level of strain, it starts to decrease again. Kobayashi [2] on the other hand found the velocity of transversal waves decrease in elastic region, yet in the plastic region they increase again. The behavior was described by the authors (and also in consequent publications [3,4]) as being a consequence of anisotropy in elastic properties and inhomogeneous localization of plastic strain, such as slip bands, creation of point defects and yield vertex which is responsible for degradation of elastic modulus.

2.1 Ratio of ultrasonic wave velocities

The inverse behavior of longitudinal and transversal waves’ velocity induced by applied stress and resulting plastic strain may be used advantageously once put together as a ratio of both measured values $c_L/c_T$ (i.e. L/T ratio). It will allow to transform the problem to a single-variable equation (only variable is the Poisson’s ratio) with monotone-increasing features.

$$\frac{c_L}{c_T} = \frac{E}{\rho (1 + \nu)(1 - 2\nu)} \sqrt{\frac{\rho}{G}} = \frac{2(1 - \nu)}{1 - 2\nu} = f(\nu)$$

This can help to determine the current stress/strain relation as was observed by Kumar et al. [5] in their article about correlation of transversal (and longitudinal) wave velocity and Poisson’s ratio. As the Young modulus $E$ and Shear modulus $G$ tend to vary in the same direction in any metal material, the variation of the Poisson’s ratio is dependent on how much each of the moduli will be affected. The range of Poisson’s ratio for isotropic solids is practically bound to $0 < \nu < 0.5$ [6]. The higher the Poisson’s ratio the less volume change during deformation.

The results of previous works [7] confirmed that there is a potential correlation between the L/T ratio and the material microstructure, and it is consistent with observations for individual velocities from abovementioned articles [1-4].

3. The experimental setup

The piping samples selected for this experiment were taken from a collapsed membrane wall from in-service combustion chamber. Samples were from pressure purpose steel (normalized P265GH TC1 / 1.0425). Chemical and hardness HV were performed on selected samples.

| Table 1: Chemical analysis results of the utilized P265GH TC1 pressure purpose steel samples. |
|-------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| P265GH TC1 | C   | Mn  | Si  | Cr  | Mo  | V   | Al  | P   | S   | Cu  | Ti  | As  | Sn  | Sb  | Nb |
| Samples MS1-4 | 0.18 | 0.43 | 0.24 | 0.06 | 0.005 | 0.005 | 0.004 | 0.015 | 0.026 | 0.03 | 0.13 | 0.005 | 0.017 | 0.009 | 0.008 | 0.005 |

Figure 1: Collapsed membrane wall from P265GH TC1 pressure purpose steel. Samples selected for this experiment are marked by arrows.
Measurement was performed on *Sonatest Sitemscan 250s* by ultrasonic pulse-echo technique. Time of flight (TOF) was measured and recalculated to ultrasonic waves’ velocity. The relative precision of velocity measurement by this method is estimated to 0.1%. Direct probe *Sonatest RDT2550* (peak frequency 4.64 MHz) for longitudinal waves and direct probe Panametrics V155 (peak frequency of 4.25 MHz) for transversal waves were used. Measurement areas were mechanically cleaned of corrosion products. On each area a mean value was collected by 10 independent measurements.

4. Results

The membrane wall piping was eccentric, with wall thickness of heat-exposed side A smaller in full length compared to the non-exposed side B. Main crack was created by creep as a result of internal pressure, heat degradation of the microstructure, and reduction of local cross-section thickness, which is in agreement with Sklenička et al. [8]. Results of L/T ratio were described in cylindrical coordinate system with \( z \) axis in the membrane main axis and \( \phi = 0 \) at the center of heat-exposed side A.

### 4.1 Sample MS-1

Sample MS-1 was straight, with right side heat-affected by oxy-fuel cutting. The closest measurement spot from the crack tip was in the distance of 150 mm. L/T ratio values on the heat-exposed side A and non-exposed side B were both around 1.85, except values close to the oxy-fuel cutting where they split with higher values on non-exposed side.

![Figure 2: Measured values of L/T ratio on marked spots of sample MS-1 (○ heat-exposed side A, ● non-exposed side B). Measurement was performed for \( \phi = 0° \), and \( \phi = 180° \) of cylindrical coordinates. Connecting lines in the chart DO NOT provide any physical relation or a trend, they are put for better orientation only.](image-url)
4.2 Sample MS-2

Sample MS-2 was visibly bent to the heat-exposed side A. Bending was most probably a result of the creep rupture and not present in the pipe during operation before the collapse. Left side was heat-affected by oxy-fuel cutting. The closest measurement spot from the crack tip was in the distance of 70 mm. At the first and the second measurement spot (from right to left) the values of heat-exposed side A reached value of L/T ratio 1.88. On the non-exposed side B the values were 1.78.

4.3 Sample MS-3

Sample MS-3 was from majority ruptured by main crack located on the heat-exposed side A. This rupture caused deformation of the surrounded area of the membrane wall piping. The wall thickness around the crack was gradually decreasing towards the crack edges.

4.3.1 L/T ratio measurement

Sample MS-3 was selected for mapping of L/T ratio development relevant to the local plastic deformation. There were 150 measurements performed on 15 different spots on heat-exposed side A divided in 3 planes perpendicular to the z axis of the sample. The first plane R1 was about 15 mm of the crack tip (on the undamaged part), R2 about 5 mm behind the crack tip and R3 about 25 mm behind the crack tip. The non-exposed side was measured the same way as on other samples.
Local L/T ratio maximums of 1.89 on the R1 and 2.03 for R2 were observed for $\varphi = 0^\circ$ coordinates. Global maximum of 2.08 was observed for $z = 60 \text{ mm}$, $\varphi = -26^\circ30'$. The L/T ratio was generally growing from all directions to the crack edge (see Fig. 4b).

### 4.3.2 Hardness testing

UJP Praha, Inc. measured hardness HV on measurement spots of sample MS-3. Main measured aspect was plastic deformation development depending on the distance from the main crack edge.

Figure 5: (a) Sample MS-3 was subject to hardness testing. Yellow numbers represent the cut planes R1, R2 and R3. Black crosses are original measurement spots for L/T ratio. (b) Yellow numbers with arrows indicate spots S1-S10 of through-thickness hardness HV measurement.
Figure 6: Hardness HV measured on planes R1, R2 and R3. (a) Hardness HV measured 1 mm under the surface, (b) mean hardness <HV> across the cross-section. Connecting lines in the charts DO NOT provide any physical relation or a trend, they are for better orientation only.

The mean hardness HV are corresponding with the L/T ratio values. Maximal values are found on spot S2, plane R3 ($\phi = -20^\circ$). For each plane the local maximum was on $\phi = 0^\circ$ and values rapidly decreased in both directions. The sharpest drop is in R1 and smallest in R3 (25 $mm$ behind the crack tip).

5. Discussion

Measurement of ratio of longitudinal and transversal waves’ velocities and its ability to react on deformation changes was tested on collapsed membrane wall from steel P265GH TC1.

5.1 Non-exposed side of tested samples

The non-exposed side B of the samples reached in all cases results with L/T ratio ranging from 1.80 to 1.85. These values are standard for structural steel samples without creep-induced plasticity, as observed in the previous work of the author [7]. Values were also always lower on the non-exposed side B than on the exposed side A. That is a result of lower heat exposure of the B which is in contact with concrete walls of the chamber that further dissipates the heat, creating different stress-strain conditions. Close to oxy-fuel cutting the values weren’t consistent due to oxy-fuel heat effect.

5.2 Samples without the main crack

Samples MS-1 and MS-2 were border samples of the extracted collapsed membrane wall. These samples were damaged by consequent deformation after the creep rupture. Sample MS-2 was visibly bent inside the combustion chamber (on the heat-exposed side A). The heat-exposed side A was subject to tension and side B was to compression. As a result the L/T ratio values were high on heat-exposed side A had maximum of 1.88 and low on the non-exposed side B with minimum of 1.78, which are already out of the standard range of values [7]. Changes in values are the most probably caused by plastic deformation of the membrane wall after the rupture, which is in agreement with articles [1,2].
5.3 Sample with the main crack

Sample MS-3 was tested in the same manner as the previous samples, but it was also selected for mapping of the L/T values distribution along the surface of the sample around the main crack. The measurement was performed on heat-exposed side A in various distances from the crack edge. It was expected that the gradient of L/T ratio would be ideally equal 0 at the center of the crack, or simply:

\[ \text{grad} \left( \frac{c_L}{c_T} \right) = 0 | \varphi = 0; z = z_0 + l/2 \]

where \( z_0 \) is the distance from the crack tip to the center of the coordinates on \( z \) axis and \( l \) is the length of the crack. Results corresponded with the expectation and the values on measurement spots close to the crack edge shown significantly increased values between 1.95 and 2.05, which was in agreement with measurements on samples MS-4 and MS-5 (which are not subject to this article). The elevated values are expected to be caused by plastic deformation. That is in agreement with articles [1-4].

Hardness HV was measured on each spot on 4 places through the thickness and hardness development was observed both along the plane cut, as well as along the wall thickness. Maximal value of steel P265GH in the as-delivered condition is HV 175 for normalized seamless pipes, yet the measurement found values above HV 190. The maximal mean value of \(<HV>\) was always at \( \varphi = 0^\circ \) and the mean hardness was decreasing with increased distance from the crack edge, similar to the L/T ratio results.

Surface hardness measurement would not provide relevant information about the current state of the piping in such situation, however the L/T ratio obviously strongly reacts on change of the stress-strain conditions with elevated values far beyond the standard values of 1.80-1.85.

Relative mean values of hardness throughout the thickness should be considered to observe the through-thickness hardness development reflecting the level of plastization. If proven that samples were only partially plasticized, the technique of measuring L/T ratio might find its utilization in detection of partially plasticized samples. This is a part of author’s current research. Its results shall be made public on upcoming conferences and in a separate article.

6. Conclusion

This article demonstrated ultrasonic waves’ velocities ratio is able to detect plastic deformation. Creep-ruptured sample was utilized to simulate various levels of plasticity. In addition the technique managed to detect areas exposed to tension or compression due to bending. The author expects to continue on this research to monitor the response of the technique to various levels of plasticity by measurement on new samples and by additional hardness testing throughout the wall thickness of existing samples.

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The base of this article may be utilized and extended to provide complete article on detection of partial plasticity by ultrasonic testing at future conferences and is planned to be published in impacted journals.

References


