INSPECTION OF SMALL PIPING CONTAINING WELD FLAWS BY IMPROVED ULTRASONIC TESTING TECHNIQUE

ZHEN-GUO YANG, LE-MIN NI* and LIN MEI
Institute of Materials Science in Mechanical Engineering,
Technical University of Munich, D-80333 Munich, Germany
**Heat Treat Department, BTR Engineering Limited,*
77 Seville Street, Fairfield Sydney, NSW 2165, Australia

ABSTRACT

An effective method of ultrasonic testing was developed for inspecting the quality of weld seams for small-calibre, thin-walled pipes. The basic technical problems encountered in measuring the height of flaws in the piping by an ultrasonic testing method were analyzed and studied experimentally. To overcome these problems, two small probes with special cylindrical contact surfaces, and five types of piping contrast specimens were machined, and a corresponding quantitative scaling method was developed. Results by both the proposed method and a practical measurement method were compared, indicating that the proposed method is effective in determining the shape of flaws in welded steel pipes.

KEYWORDS

Ultrasonic testing, weld flaw, small piping, inclined probe, wave amplitude method, integrity assessment.

INTRODUCTION

Ultrasonic testing is one of the most promising approaches to examining the quality of joints in piping in service. There are currently standards for detecting and measuring the size of weld seam flaws in large-calibre steel piping, such as cracks, lack of penetrations, incomplete fusions, and slag inlusions. In steel piping, however, standardized ultrasonic inspection is limited to pipes with a diameter, ϕ, greater than 250 mm, and a wall thickness, t, greater than 6 mm (Robent, 1985), as smaller calibre piping present additional complications. Unfortunately, a large percent of process piping used in chemical plants are usually small-calibre, thin-walled piping. Taking the Shanghai Petro-chemical Complex as an example, more than two thirds of the piping for chemical process usage have a diameter of less than 250 mm or a wall thickness of less than 6 mm. The problem of assessing the structural integrity of such piping in service, and being able to determine whether pipes with flaws should be repaired, replaced, or left in service *as is* is a practical challenge for engineering.

The present paper will summarize the problems that arise in the ultrasonic inspection of small-calibre piping, and describe an inspection method based on the Wave Amplitude Method which accounts for the added complexity of inspecting small-calibre pipes. The method has been adopted as part of a comprehensive safety assessment program by several chemical plants around Shanghai, China (Yang et al, 1991; Yang, 1995).

EXISTING PROBLEMS

Why are conventional ultrasonic testing methods not suitable for detecting the depth of flaws in small-calibre piping effectively? The main reasons are as follows:

(1) Diffusion of sonic energy travelling through a piping wall when the ultrasonic beam transmits from the outer wall of a pipe to inner wall of a pipe. Not only can the refraction wave produce certain diffusion phenomena (c_1=2720 m/s, c_2= 3100 m/s), due to the small radius of curvature, but also the reflection wave becomes more severe with the decrease of the piping diameter, as shown in Fig.1. These factors can seriously influence the sensitivity of ultrasonic testing.

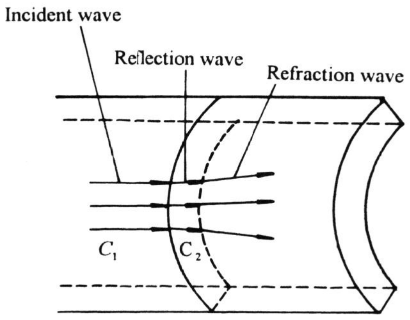

Fig. 1 Loss of sonic energy through pipe wall

(2) A consequence of a thin pipe wall is that in order to avoid the severe diffusion of sonic energy, the inspected zone is usually located within the first half of the near-field zone of the ultrasonic wave when the primary and secondary waves of a conventional probe are used to inspect the weld seam of small piping. The effect of the near-field zone in thin-walled piping can greatly reduce the sensitivity of ultrasonic testing.

(3) Ultrasonic testing of thin-walled pipes is not as sensitive to rounded inclusions, such as gas pockets or slag inclusions in welded metals or voids in composites, and the difficulty of detecting such flaws is increased by the combined effect of near-field zone and the loss of sonic energy.

(4) The contact surface of conventional probes does not fit well with the outer wall of small-calibre piping, which will also greatly affect the accuracy of the measurement of the ultrasonic testing.

In summary, some serious obstacles exist for ultrasonic testing of small-calibre piping. In the next section, a method will be presented for overcoming these obstacles.

ULTRASONIC INSPECTION FOR SMALL-CALIBRE PIPES

In this section two improvements in the ultrasonic inspection of pipes are described, which overcome the above-mentioned problems inherent with small-calibre piping. First, the head of the ultrasonic probe is reshaped, in order to allow to better contact with the pipe. Second, specimens with flaws resembling natural flaws are machined. These specimens are used to calibrate the ultrasonoscope for use on actual piping.

Improving the Structure and Contact Surface of the Probe

In order to insure good accoustic coupling between the ultrasonic transmitter and the specimen, the piezoelectric probe head and the specimen surface must mate well. For small-calibre pipes, this means that typical ultrasonic probe heads must be machined to have a convex surface. For piping with an outer diameter ϕ it was found that adequate coupling could be acheived with a normal grease coupling agent if the radius of curvature of the probe head is machined to R= (1.1-2.0)× ϕ /2, thus allowing one probe head to be used on a range of pipe sizes.

Theoretical Analysis

After reshaping the probe head to insure adequate contact between the ultrasonic probe and the test specimen, the ultrasonic signal can be analyzed. The formula for calculating the near-field zone length of an inclined probe, N (Yun, 1982 and see Fig. 2) is

$$N = \frac{ab\cos\beta}{\lambda_{s_2}\cos\alpha}$$

in which a and b are the dimensions of the inclined probe's contact surface, β is the refraction angle of the sonic wave in the test specimen, α is the incident angle of the sonic wave in the wedge, and λ_{s_2} is the transverse wavelength in the specimen.

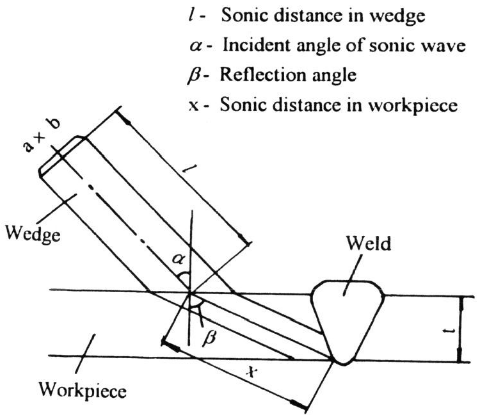

Fig. 2 Sonic distance in the wedge and workpiece

Figure 2 illustrates the geometrical relationship between the sonic distance of the wedge and the specimen. If the inclined probe with small crystalline piece is used, for example, conventional model ,5.0 p 8×8, k=3.0, then N is 52 mm according to the above formula. The sonic distance, l =18 mm, is then measured from the standard specimen of the ultrasonic testing. If the wall thickness of the inspected piping is t=4.2 mm, the path length of the primary wave travelling from the incident point to the root of the weld seam is x=12.6 mm, as depicted in Fig. 2. Under such circumstance, the necessary condition, N/2 -l 〈 x, is satisfied if the weld seam of a small-calibre pipe is detected by the primary and secondary sonic waves of the probe, so that the ultrasonic wave arriving at the root of the weld seam lies at the far-field of the latter part of the sonic field. It is, therefore, assured that the influence of the near-field zone and loss of sonic energy can be overcome if the weld seam of small piping is detected by the primary and secondary waves (Robent, 1985; Yun, 1982).

Judgement of Wave Patterns on the Screen of the Ultrasonoscope

The ultrasonoscope needs to be calibrated so that a technician can correctly interpret its signal during testing. For simplicity, specific zones which correspond to the dimensions of the artificial in the test specimens were marked on the ultrasonoscope screen itself, enabling a technician to quickly and accurately assess the inspection results. An example of the ultrasonoscope screen is given in Fig.3.

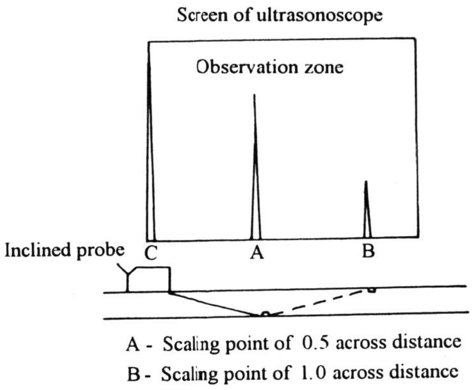

Fig. 3 Schematic diagram of mark point observation zone

Two points, at 0.5 and full length across the horizontal axis of the ultrasonoscope screen, are labelled on the screen itself, dividing the screen into two regions, one between the 0.5 and 1.0 marks, and other to the left side of the 0.5 mark. Now, if a refraction wave appears in the left zone, it is judged as a signal from a flaw. A refraction wave appearing at the zone between 0.5 and 1.0 marks may represent a flaw, or it may represent a normal geometrical refraction. It is taken to indicate a flaw if the primary wave does not enter the weld seam, otherwise, it is a geometrical refraction waves. For the flaw signal appearing very near the 0.5 mark, the flaw lies on the root of the weld seam. A flaw signal appearing near the 1.0 mark indicates a flaw lying near the upper surface of the weld seam. If a signal from a flaw appears in any other place in the observation zone, the flaw lies somewhere in the middle of the weld seam.

Making Contrast Specimens and Determining the Height of Artificial Flaws by the Wave Amplitude Method

Our experience shows that most of the flaws existing in the weld seam of small-calibre piping are incomplete fusions of shallow depths . As a result, when the ultrasonic testing is used to examine the weld seam of small-calibre piping, although the length of the incomplete fusion and other kinds of flaws can be detected by the 6 dB method, it is not suitable for determining their height (i.e. the length of the flaw through-the-thickness of the pipe wall) if their height is less than 3.2 mm (Yun, 1982; Robent, 1985), which is almost always the case in thin-walled pipes. Instead, we used the Wave Amplitude Method, in which artificial flaws are machined in pipe sections cut from the actual process piping to be examined.

As the application of the Wave Amplitude Method is still not very popular, there are still not benchmark test specimens as well as the corresponding standards available for the ultrasonic testing of small-calibre piping. Consequently, an important task of the paper was to make piping contrast specimen and to work out corresponding quantitative estimation methods of the flaw and a scaling for the ultrasonoscope sensitivity. The procedures are given below.

(1) A segment of the actual piping to be inspected is cut off and removed for examination. Slots of different depths are machined on the inner and outer walls of the piping, as artificial flaws which resemble cracks. The slots are all 1 mm wide and the distance between each slot is 10t, in which t refers to the wall thickness. The slot depths are taken to be 0.10t, 0.15t, 0.20t and 0.30t, respectively, as shown in Fig. 4. These slotted specimens are the contrast specimens of the corresponding piping for calibrating the ultrasonic test apparatus. Additional specimens are drilled with two small holes of ϕ=4 in the inner and outer walls, respectively. They are used as the quantitative contrast specimens for volume-type flaws, such as voids and gas holes.

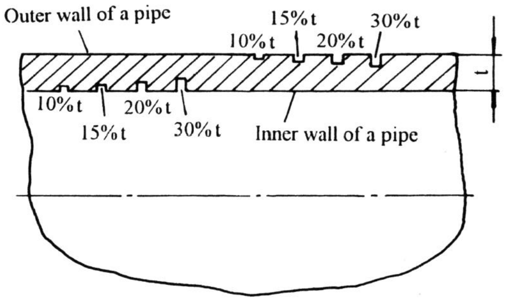

Fig. 4 Schematic diagram of pipe contrast specimen

(2) The reshaped probe head mentioned above is used. The ultrasonoscope scaling is adjusted first. The attenuation and the gain are then adjusted. On the condition of maintaining about 30 dB drooping margin, the scaling which makes the maximum echo height of the 0.15t slot achieve 50% of the full scale is taken as that of sensitivity degree. At this condition of sensitivity degree, the primary wave is used to detect the other slots, and its maximum echo height location is labelled on the ultrasonoscope screen. Then the secondary wave is used to detect external slots of various depths and the location of maximum echo heights from the these slots are also labelled on the screen.

Afterwards, a line is drawn between two echo height points of slots with the same depth. A horizontal line is then drawn to the left zone of the 0.5 mark. Thus the distance wave amplitude curves of slots with various depths, which are also distinct curves of echo height, is created, as shown in Fig. 5. A similar curve of echo height for the artificial hole is made on the ultrasonoscope screen, as illustrated by the broken line in Fig. 5.

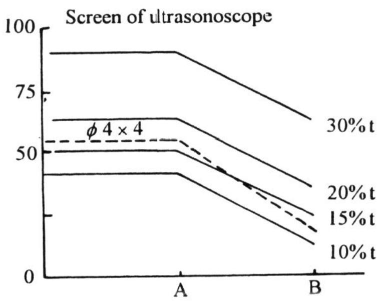

Fig. 5 Distinct curve of echo height for artificial flaw

(3) During the ultrasonic testing, if only the echo heights of plane-type flaws are detected (such as incomplete fusions or cracks), the upper and lower limit of the height of the detected flaws can be determined by comparing wave amplitude of the flaw signal to the echo wave amplitude of the artificial flaws in the contrast specimens with reference to the echo height distinct curve. If a more accurate measurement is needed, it can be estimated based on the attenuation number in dB of its corresponding artificial flaw. Numerous of experimental results showed that the echo height of incomplete fusions and cracks which are longer than 6 mm is related to the dB number of a similar artificial flaw. This correlation was found to be (Yun, 1982)

$$\mathrm{dB} = 20 \log \frac{h}{h_o}$$

in which h and h_o refer to the height of the flaw and of the artificial flaw, respectively. For volume-type flaws, the curve of the echo height is found from the small hole ϕ 4 mm × 4 mm contrast standard. In order to be assured of a conservative estimate of the residual load-bearing ability of defective pipes, the height of flaws are taken to be the upper limit of the height measured on the ultrasonoscope.

EXPERIMENTAL RESULTS AND DISCUSSION

The following experimental program was carried out: The two kinds of small probes with different inclined contact surfaces were first machined. Five types of pipe contrast specimens were then made. The relavant parameters of specimens are listed as follows:

The length of the specimens are 300 mm, and the other dimensions are ϕ 60 × 4.0, ϕ 89 × 5.0, ϕ 108 ×4.5, 114 × 5.5, ϕ 165×7.1, (mm × mm), respectively. One of the two reshaped small probes is 5.0 p8 × 8, with k=3.0, curvature radius of the contact surface R=50 mm, while the other is 5.0 p8 × 8, k=3.0, and R=90 mm, respectively. The probe with curvature radius R= 50 mm is used to measure pipings of ϕ 60 and ϕ 89, and the another probe with curvature radius R= 90 mm is used to measure pipings of ϕ 108, ϕ 114, and ϕ 165.

All contrast specimens for pipings were taken from old waste pipings removed from the actual pipelines during heavy repair in the Shanghai Petrochemical Complex. Three kinds of butt welds for pipings, i.e. ϕ 60 × 4.0, ϕ 89 × 5.0, ϕ 108 ×4.5, were chosed to conduct an ultrasonic testing, and then the weld region was cut and dissected; and finally the height of the flaw was determined by mechanical measurement. These mechanical measurements were used to compare to those measured from the proposed ultrasonic testing.

The ultrasonic testing equipment used in the present study was Model CTS-22 ultrasonoscope and the coupling agent was chemical paste. The surface of the weld seam needs to be polished before inspecting. A comparison of the results obtained by the ultrasonic testing method and mechanical measurements are listed in Table 1 for three sizes of pipes.

Table 1 Comparison of dimensions of real flaws measured by ultrasound and then mechanically on dissected pipes

Pipe dimension (mm × mm)	Ultrasonic testing method *h* (mm)	Mechanical measurement *h* (mm)	Relative Error (%)
ϕ 60 × 4.0	0.4	0.38	5.3
ϕ 60 × 4.0	0.6	0.57	5.2
ϕ 60 × 4.0	0.8	0.77	3.9
ϕ 89 × 5.0	0.5	0.48	4.1
ϕ 89 × 5.0	0.75	0.72	4.2
ϕ 89 × 5.0	1.0	0.98	2.0
ϕ 108 × 4.5	0.5	0.47	6.3
ϕ 108 × 4.5	0.7	0.67	4.4
ϕ 108 × 4.5	0.9	0.87	3.4

Remark: h *is denoted as the height of a flaw, and the relative error is computed with respect to the mechnical measurement method.*

It is seen from table 1 that the results obtained from the ultrasonic testing method are in good agreement with those obtained from actual physical measurement. The relative error of the ultrasonic test method was approximately 5% for real butt welding flaws. In addition, the larger the height of a flaw, the smaller the error in the ultrasonic measurements, so that the ultrasonic method can be expected to be more accurate at measuring the largest and thus most critical flaws. These results prove the validity of the proposed ultrasonic method. This method has been successfully applied as part of a general safety assessment program for the structural integrity assessment of the pressure vessels and pipings with weld flaws in the Shanghai Petrochemical Complex, and several other chemical plants near Shanghai (Yang et al,1991; Yang, 1995).

CONCLUSIONS

A method for the detection of weld flaws in small-calibre pipes in service was introduced. The method consists of a modified ultrasonic probe and an ultrasonoscope specially calibrated on test specimens machined to have flaws similar to the crack and volume-type flaws observed in actual flawive piping. The method accurately measured the dimensions of flaws when compared to mechanical measurements made by dissection of pipes removed from service, and has already been incorporated into a comprehensive safety assessment plan used by several chemical factories on carbon and stainless steel piping, and has potential applications for fiber-reinforced plastic piping.

REFERENCES

Roben, L. M. (1985). *Annual Books of ASTM Standards*, **Vol.03.03**.

Yang, Z. G. et al. (1991). Safety Assement for Combustible and Explosive Chemical Process Pipeline Containing Weld Flaws in Service, *J. Chinese Safety Science*, **1**(2), 34-41.

Yang, Z. G. (1995). Safety Assessment of Polyester Polymerized Tower with Weld Cracks, *Synthetic Fiber Industry* **18** (4),37-41.

Yun, Q. H. (1982). Non-Destructive Testing, pp243-428. Labour Publishing House, Beijing.