ABSTRACT

Cast iron parts of water supply and drainage pumps are usually used under corrosive environments and graphitic corrosion develops in the areas near water-air interface. In this paper, a methodology for the quantitative evaluation of graphitic corrosion from the outer surface of pumps by ultrasonic pulse waves is described. Pulse waves generated by an emitter/sensor on the outer surface are reflected from the corroded inner surface and the height of the echo, which is monitored by the emitter/sensor, is a function of the corrosion condition. Based on the field data of 16 cases of pump parts, master curves are developed for the relation of graphitic corrosion condition and the pulse echo ratio. Corrosion condition of a pump parts is evaluated by the proposed method and also by observations of the inner surface after disassembly of the pump. Comparison of these results showed a good agreement.

INTRODUCTION

Cast iron is widely used for water and wastewater equipments because of its superior properties in durability, machinability, high ability of vibration damping and so on. In particular, gray cast iron is almost always used in body sections of important pump equipment between the suction and discharge sides. However, after years of usage in waters with corrosive substances and repeated exposure to air, the inner surfaces of the body of such equipments heavily corrode. Corrosion of gray cast iron is called as graphitic corrosion and is typical in pump parts under repeated starts and stops.

Inner and outer surfaces are usually coated with a lining material that prolongs their corrosion resistance, but when these coatings are lost after degradation, electrochemical cell is formed on the surfaces where the cast iron matrix (ferrite-cementite phase) works as anode while the particles of graphite and steadite, which is formed in the material after phosphorization, serve as cathodes.

This results in graphitic corrosion whereby the cast iron matrix is selectively dissolved and gradually leaches out into the water, leaving behind the graphite and steadite. Since the graphite and steadite are left behind, the inner surfaces of the pump do not look eroded, but are weakened to the point where they can easily be cut with a knife. Consequently, graphitic corrosion eventually leads to penetration, causing problems such as leaks and loss of parts.

To maintain the reliability of pump equipments, periodical examination of inner surfaces is needed but it is often impossible to identity the status of corrosion visually due to a lack of adequate installations such as manholes. Lime scales or other contaminations on the inner surfaces also make it difficult to examine visually even if there are installations for visual check. X-ray is sometimes used as a more reliable check for corrosion inside pumps, but this involves practical difficulties. For example, due to the wall thickness of pumps and the shape of their internal component parts, X-ray of the high energy is needed to reliably check for internal corrosion. Also, it can be troublesome to construct suitably managed work environments where X-rays can be used safely. As a result, X-rays are usually impractical for in-situ corrosion measurements. Ultrasonic is widely used for the evaluation of wall thickness, but it was not used for the identification and assessment of corrosion. Therefore, it has been necessary to periodically disassemble pumps and clean the internal surfaces to reveal the grain of the metal so that the state of corrosion can be judged visually. This is a costly and time-consuming process.

To perform the maintenance of pumps in a systematic and efficient way, an in-situ method to check the state of corrosion and wall thickness of each component should be established. Although some techniques for the evaluation of corrosion and degradation of pump parts were reported in earlier studies, these techniques were only applied to dismantled pumps and evaluation of corrosion and degradation were not quantitative. Measurement technique of specimen thickness by pulse reflection...
time of ultrasonic wave is well established and this technique is hopeful also for the measurement of corrosion status of pump parts.

In this paper, we use ultrasonic wave and develop new techniques for the in-situ measurement of wall thickness of cast iron components of pump parts and the corrosion status are evaluated from the data of reflected ultrasonic wave.

PRINCIPLE OF MEASUREMENT BY ULTRASONIC PULSE ECHO TECHNIQUE

Ultrasonic waves have various properties such as diffusion, attenuation and reflection/refraction at acoustically discontinuous interfaces. When an ultrasonic pulse enters a not corroded test piece of gray cast iron with parallel surfaces and not corroded, reflected waves with gradually decreasing intensity are received at equal time intervals.\(^{(3)}\) On the other hand, in gray cast iron with advanced graphitic corrosion, the ferrite/cementite phase dissolves away to leave a rough corroded surface made of graphite and steadite. The graphite and steadite are almost completely transparent to ultrasonic, so as shown in Fig.1, when the ultrasonic reaches to the corroded inner surface of the cast iron, the ultrasonic is reflected from the interfaces between the regions of corroded gray cast iron and regions where the not corroded microstructure is still intact. If the wall thickness of the parent material is reduced as a result of corrosion, then the reflected wave will reach the sensor sooner than it would have done otherwise. This means it is possible to estimate the wall thickness from the time taken for the incident ultrasonic waves to return to the sensor. Section 3 describes this technique in detail.

On the other hand, since the ultrasonic is diffused by the large indentations that form due to corrosion, it is thought that the intensity of the reflected waves will be smaller than for a not corroded surface. It should therefore be possible to evaluate the state of corrosion on internal surfaces by determining the correlation between the attenuation coefficient (the intensity ratio of the incident and reflected waves) and the degree of corrosion. However, the intensity of the reflected waves is also affected by how well the sensor makes contact with the test piece.

So in this study, instead of using the intensity ratio of the incident and reflected waves, we investigated a method that uses the height ratio \(R\) of the first reflected wave (first

\[ R = \exp(-2\alpha T) \]  

Figure 1 - Reflection of ultrasonic wave from flat (a) and corroded (b) inner surface of cast iron.

In general, the acoustic pressure \(A(x)\) of an ultrasonic wave propagating through an elastic medium obeys the following relation:

\[ A(x) = A_0 \exp(-\alpha x) \]  

where \(A_0\) is the initial acoustic pressure, \(x\) is the propagation distance, and \(\alpha\) is the attenuation coefficient.\(^{(4)}\) For not corroded material, Echo height ratio \(R\) when sonic waves are incident from the surface and reflected from the inner surface to the sensor can be calculated from the following expression assuming there is no attenuation

\[ R = \exp(-2\alpha T) \]  

(a) Flat  (b) Corroded
where the sonic propagation distance is \( 2T \) (i.e., twice the wall thickness \( T \)).\(^{(5)}\) Using this expression, we collected data on the relation between the wall thickness \( T \) and echo height ratio \( R \) using actual not corroded pump parts with different thicknesses, and hereby calculated the attenuation coefficient \( \alpha \) of not corroded cast iron parts. Using this value of \( \alpha \) we determined the relation between the wall thickness \( T \) and echo height ratio \( R \) as a reference curve for sound cast iron parts.

We also performed the same measurements on materials with advanced graphitic corrosion. By comparing the resulting measurement data and the results of observing the corroded surfaces, we compensated the attenuation coefficient\( \alpha \) for corroded materials. Since the degree to which \( \alpha \) needs to be compensated depends on the degree of corrosion, this is used to add a reference line to the degree of corrosion damage, and in this way we constructed master curves that can be used to estimate the degree of corrosion from the relation between the wall thickness \( T \) and echo height ratio \( R \). The details of this technique are described on later. To construct this data, we need to make accurate measurements of wall thickness and collect data with little variation relating to the echo heights. We therefore conducted a preliminary experimental study of measurement methods.

**PRELIMINARY TESTS AND VERIFICATION OF TECHNIQUE**

**Examination of echo height measurement by sensor contact method.**

Figure 2 shows the experimental measurement system. This system mainly composes an ultrasonic sensor, an ultrasonic detector, an oscilloscope and a PC which is used for data processing. For metals like cast iron that have a rough surface and a non-uniform composition, it is harder to pick up the reflected waves. Ultrasonic sensor applied wide-band 1MHz, \( \phi 19 \text{mm} \).

When using ultrasonic for wall thickness measurements and flaw detection, unless the measurements are performed automatically, the person making the measurements usually has to manually bring the sensor into contact with the article being measured. The resulting contact state can affect the intensity of the reflected waves. A contact medium with high acoustic impedance (e.g., glycerin paste) is applied to reduce the attenuation of ultrasonic at the contact surface, but if this layer of contact medium is too thick then the ultrasonic will be attenuated inside the contact medium and the intensity of the received echo waves will be reduced. On the other hand, if the sensor is pressed too hard against the object being measured, then the vibration will be restricted in the vicinity of the transducer and the echo intensity will be reduced. It is also thought that the echo intensity differs depending on how rough or uneven the surface of the object is.

Therefore, in order to allow manual measurements to be performed in a stable way, we inserted a stiff transparent plastic film (0.1 mm thick) between the sensor and the surface of the measured object as shown in Fig.2, and we determined the relation between the contact pressure and the reflected echo height.

**Verification of echo height measurements**

To investigate the effects of contact pressure on the echo height and the effects of inserting the plastic film, we performed measurements of the first echo height while varying the sensor contact pressure. Since the measurement gain was different in each case, the measurements were compared by normalizing the largest first echo measurement to a value of 1. The results are shown in Fig.3. With the film inserted, the echo height is less affected by the contact pressure. This is thought to be because placing the film and contact medium between the sensor and the object being measured makes the measurement less susceptible to the effects of surface roughness, and even with a small contact pressure it forms a close contact so that the received waves are less likely to depend on the contact state of the sensor. The film used in this study was printed in advance with measurement areas and measurement gaps which were used in positioning of the measurement point. By this, it is thought that the accuracy of the measurement position rises was also considered.
CONSTRUCTION OF CORROSION DIAGNOSIS MASTER CURVES

We disassembled sixteen vertical type pumps used from a few years to a few decade in age, and using the measurement system shown in Fig.2 and the methods discussed in the above, we measured the wall thickness and echo height ratio at the cast iron discharge casing. The measurements were made in a 200 mm × 200 mm area (measurement area 180 mm × 180 mm) which was partitioned into 10×10 smaller areas with a grid spacing of 20 mm, within which the wall thickness distribution and echo height ratio were measured at 100 points.

Visual observations were also made of the actual state of corrosion on the inner surface after peeling away the paint. Figure 4 summarizes the results of measuring the average echo height ratio and wall thickness. In the visual observations, the state of corrosion on the inner surface was classified into three levels — not corroded, roughened (initial stages of corrosion), and heavily corroded. Compared with cases where the inner surface was not corroded, the echo height ratio was smaller in cases where the inner surface was roughened or in a state of advanced corrosion. When the inner surface was corroded to the point where it had become very uneven, the echo height ratio was even smaller. These results demonstrate a clear correlation between corrosion and the echo height ratio.
From the wall thickness, echo height ratio and corrosion state observation results, we analyzed in detail how the echo height ratio $R$ varies with the degree of corrosion, and we constructed master curves for judging the state of corrosion by correcting the attenuation coefficients according to the degree of corrosion damage. The results are shown in Fig.5, where the wall thickness and echo height ratio are shown on the horizontal and vertical axes respectively, and the numbers on the curves represent the corrosion levels. The boundary line of the not corroded region was formed by using expression (2) to determine the attenuation coefficients from the measurement data of regions with a not corroded inner surface. For the threshold lines in corroded regions, the degree of corrosion was divided into five stages, and the curve for each corrosion level was drawn by determining the attenuation coefficient that best fits the measured values of the reflected echo height from the inner surface. The region for corrosion levels of 5 and above represents cases where pronounced corrosion and erosion had occurred.

Based on the above method, we developed a corrosion diagnosis system that can easily be used for in-situ pump inspection. The diagnosis system comprises a 1 MHz ultrasonic probe, a digital ultrasonic flaw detector, and a PC with a stylus input to make it easier to use on site. The PC handles the input of measurement settings, analyzes the waveforms obtained from the flaw detector, and processes the corrosion and wall thickness diagnosis results. This system is designed for use with cast iron (FC), and can measure wall thicknesses ranging from 10 to 50 mm with a resolution of 0.2 mm. The diagnosis procedure is as follows: a measurement grid is printed in advance on the outer surface of the object in question, a transparent film is stuck on, measurements are performed in each partitioned area, and the corrosion levels and wall thickness values are obtained based on the master curves shown in Fig.5. Based on these results, contours of equal inner surface corrosion level and wall thickness are drawn up.
VALIDATION OF AN ACTUAL PUMP EQUIPMENT

To verify the validity of this technique on actual equipment, we used it to diagnose the wall thickness distribution and inner surface corrosion state in part of the discharge casing in a vertical type pump shown in Fig.6, and we then took the pump apart and compared our findings with the results of observing the inner surface. The measurement and diagnosis results are shown in Fig.7 and 8. The wall thickness inside the measurement region was approximately 27–35 mm (Fig.7), and the degree of corrosion was distributed over the range from not corroded to corrosion level 5 (severely corroded and eroded) (Fig.8).

Figure 9 shows a photograph of the inner surface observed when the pump had been disassembled. By comparing the actual corroded inner surface with the wall thickness distribution estimated by ultrasonic diagnosis, we found that the two were more or less identical, including large areas of corrosion and erosion at the upper left and lower central areas. Therefore we confirmed that this technique could be used to estimate and evaluate the wall thickness and inner surface corrosion state of gray cast iron components without having to take them apart. We performed similar ultrasonic diagnosis and physical disassembly/visual observation tests on 260 pump parts. In each case, the results were more or less identical with regard to the internal corrosion state.

Figure 6 - Discharge casing of a vertical type pump and the measured area.

Figure 7 - Distribution of estimated thickness.
CONCLUSION

We have investigated a method for estimating the wall thickness and inner surface corrosion of gray cast iron pump parts by making measurements from the outside. As a result, our conclusions are as follows:

As a method for evaluating the degree of corrosion on the inner surface of parts, we investigated the relation between the variation of echo height ratio with wall thickness and the corrosion data from actual equipment, and we produced corrosion diagnosis master curves. Based on these master curves, we diagnosed corrosion and erosion in a number of pump parts, and when the actual state of corrosion was checked by taking the pumps apart, the diagnosis results were found to closely match the actual corrosion state. We have therefore confirmed that this technique is a useful way of evaluating corrosion without having to disassemble the equipment.

REFERENCES

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