Recent Developments in UT Diagnostic Technology

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Abstract:

JFE Steel West Japan Works (Fukuyama) developed wear diagnostic technology for gear coupling using ultrasonic flaw detection technology and diagnostic technology for chimney iron skin for the purpose of soundness evaluation of equipment. The wear diagnostic technology of the gear coupling enables quantitative and accurate diagnosis of the wear amount of the tooth surface from coupling outer cylinder. In addition, the chimney diagnosis device can freely travel on the surface of the chimney with a wireless inspection dolly and measure the wall thickness. We contributed to the stable operation of the facility by making practical use of developed diagnostic technology and making effective use at the site.

1. Introduction

In maintenance of the component members of ironmaking facilities at JFE Steel West Japan Works (Fukuyama), soundness and safety are evaluated by using non-destructive inspection (NDI). Concretely, UT (Ultrasonic Testing) is used in evaluations of welds and axial members, and abnormality evaluations are carried out based on the presence or absence of internal defects. In addition, new flaw detection methods such as weld inspection of tanks by TOFD (Time of Flight Diffraction) and crack inspection of axial step parts by phased array ultrasonic inspection method have also been applied practically.

However, NDI could not be applied to equipment which is dismantled for inspection, beginning with gear couplings, and large equipment such as chimneys due to the time and cost required for inspections. Therefore, JFE Steel developed technologies using UT inspection, which enables inspection of the condition of the equipment by thickness measurement.

This report describes the development of a wear diagnostic technology by measurement of the tooth thickness of gear couplings and a chimney diagnostic system that enables free measurement of the thickness of the chimney steel shell.

2. Development of Wear Diagnostic Technology for Gear Couplings

2.1 Features and Measurement Principle of UT

Figure 1 shows the reflection properties of ultrasonic waves. When a longitudinal ultrasonic wave enters in a specimen, the ultrasonic wave that advances from the transducer in the vertical direction is divided into a bottom echo, which is reflected from the bottom, and a delayed echo, in which the ultrasonic wave is delayed by diffusion before detection. The delayed echo is formed by a repeated process in which the longitudinal wave which diffuses during incidence is reflected by the wall and undergoes mode conversion to a shear wave, and then undergoes a further conversion to a longitudinal wave when it is reflected by the wall on the opposite side of object of measurement. This causes a delay in the time until the wave returns to the transducer in comparison with the bottom echo. The difference in the beam paths of the bottom echo and the delayed echo ΔWn can be expressed by Eq. (1).

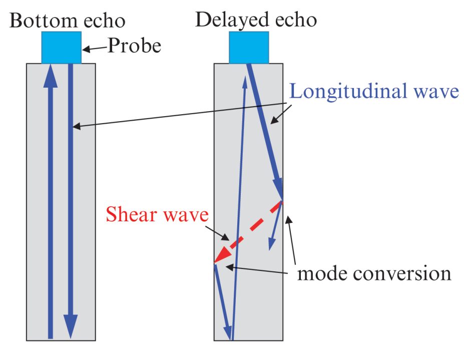

Fig. 1 Reflection route at ultrasonic incidence

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$$\Delta Wn = \frac{n \cdot d}{2}\sqrt{\left(\frac{C_L}{C_S}\right)^2 - 1} \quad \cdots\cdots (1)$$

where, d is the thickness of the specimen, C_L is the sound velocity of the longitudinal wave in the specimen, C_S is the sound velocity of the shear wave in the specimen, n is the number of times the delayed wave crosses the width of the specimen, and means the echo that appears at the n-th time counted from the time of bottom echo. From Eq. (1), a proportional relationship exists between the thickness d in the specimen and ΔWn. Therefore, it is possible to obtain the thickness d of the specimen by measuring ΔWn. Although the above explanation is based on a rectangular surface, mode conversion also occurs in the same manner, generating a delayed echo, when the object of measurement is trapezoidal, as in the teeth of gear couplings and spline couplings.

2.2 Verification of Reflex Pathway by Full-Scale Model

The reflex pathway was verified by using a gear tooth verification model (gear module: 6, pressure angle: 20°) having the relationship between the reflex pathway of the above-mentioned delayed echo and the tooth thickness shown in **Fig. 2**. An incident ultrasonic wave from the upper edge face of the specimen (opposite side from tip of gear tooth) toward the tooth tip undergoes diffusion with a certain divergence angle depending on the characteristics of the transducer and the ultrasonic wave. The divergence angle ϕ_0 of the ultrasonic wave undergoing diffusion can be obtained by Eq. (2).

$$\phi_0 \fallingdotseq 70\frac{\lambda}{D} = 70\frac{C}{Df}\ (°) \quad \cdots\cdots (2)$$

where, D is the diameter of a circular oscillator, λ is the wavelength of an ultrasonic wave, C is the speed of sound and f is frequency. It can be understood that the divergence angle is inversely proportional to the oscillator diameter and directly proportional to the wavelength. Thus, if the divergence angle is increased by using a small probe, the incident wave will be reflected by the tooth surface, generating a delayed echo. An A scope image at this time is shown in **Fig. 3**.

If the amplitude of the reflected wave is plotted on the y-axis and time is plotted on the x-axis, the delayed echo is detected by the delay from the bottom echo. The difference of the beam path lengths of this bottom echo and delayed echo is ΔWn. **Figure 4** shows the ultrasonic reflection routes and intensities for an incident ultrasonic wave in a gear tooth. The reflection route of the bottom echo is the shortest route which is reflected by the end face of the tooth, and in case the end face is sufficiently wide, the intensity of reflection is 1. Although an infinite number of delayed echo routes are conceivable, among those routes, the route that is closest to the bottom echo and also has the highest sound pressure was obtained by a simulation.

In this delayed echo route, first, the wave is reflected by one side surface near the tip of the tooth. As a result, the wave undergoes mode conversion to a shear wave, and attenuation to 0.85 occurs. This is followed by specular reflection by the tooth end face, and then mode conversion to a longitudinal wave at the other side surface near the tooth tip, and the wave returns to the transducer after further attenuation to 0.68. It is

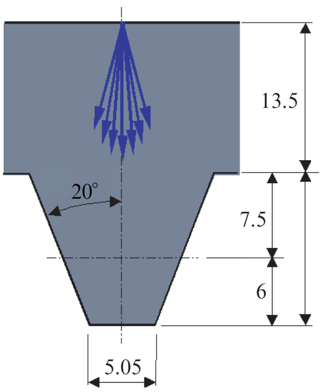


Fig. 2 Verification model (module 6)

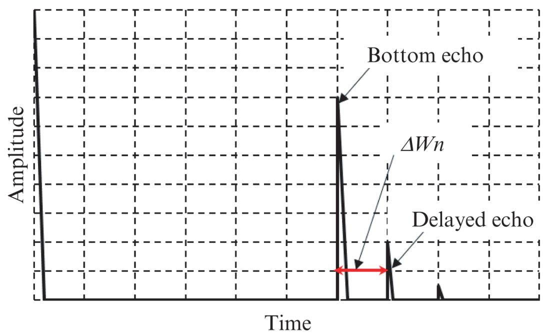


Fig. 3 A scope inspection image

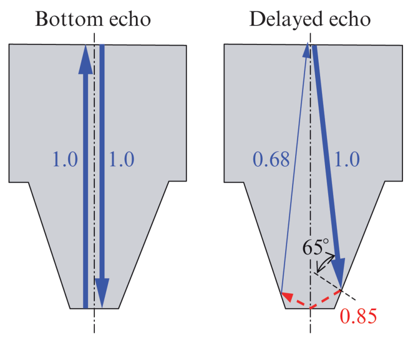


Fig. 4 Ultrasonic reflection route

possible to measure the thickness of the tooth from this detected echo.

Next, **Fig. 5** shows the relationship between the difference of the beam path lengths of the bottom echo and delayed echo for the tooth thickness. In condition A, when the tooth thickness is thick, the difference between the beam paths of the bottom echo and the delayed echo is large. As wear proceeds and the tooth becomes thinner, the condition changes from B to C, and the difference between the beam paths of the bottom echo and the delayed echo becomes smaller. This relationship between the tooth thickness and the beam path difference can be calculated geometrically. **Figure 6** shows an example of a conversion table in which the tooth thickness and the beam path difference are obtained geometrically.

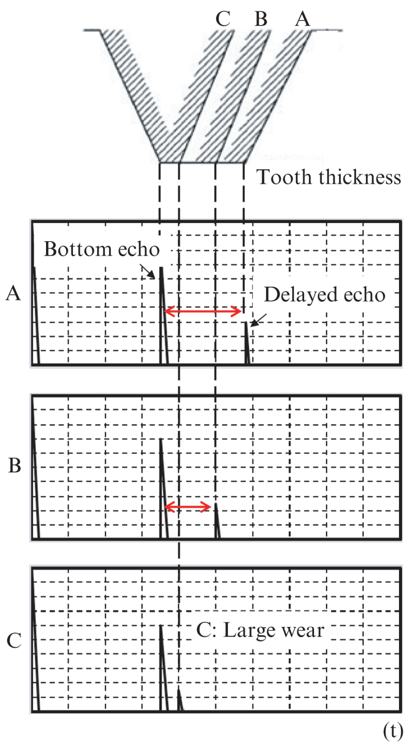


Fig. 5 Relationship between the bottom echo and delay echo

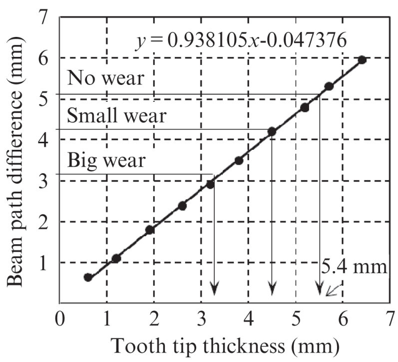


Fig. 6 Conversion table of tooth tip thickness and beam path difference

Although the slope of the line will differ depending on the gear module and the tooth dimensions of the pressure angle, a first-order linear relationship exists between the tooth thickness and the beam path difference. The conversion table shown in Fig. 6 is for the case of tooth profile dimensions of module: 8, pressure angle: 20, tooth depth: full depth tooth, thickness of rim: 27 mm and number of teeth: 71. The wear condition of gear couplings of the same dimensions can be evaluated based on measurements of the beam path difference by using this table.

2.3 Device Composition

An image of ultrasonic testing of a gear coupling is shown in **Photo 1**. The device composition comprises an EPOCH 1000 for obtaining phased array ultrasonic inspection method images as the flaw detector and a 5L16 phased-array probe as the transducer (both manufactured by Olympus Corporation).

2.4 Accuracy Verification by Specimen Measurement

Accuracy was verified by using specimens with three different gear modules (4, 6, 8). Conversion tables were prepared based on the specifications of each specimen, and the beam path difference, ΔWn, was measured by placing the transducer on the outer diameter surface. The measurement results for the respective specimens are arranged in **Table 1**. The graphs show the actual tooth thickness on the x-axis and the measurement results on the y-axis.

As can be understood from the measurement results, measurement with good accuracy is possible when the actual tooth thickness is larger than 2 mm, but accuracy decreases with 2 mm or less. As the estimated cause of the decrease, because the tooth tip is narrow, it was not possible to separate the bottom echo and the delayed echo due to the characteristics of the ultrasound wave (frequency, diffusion loss, etc.). Excluding 2 mm and under, measurement accuracy was $2\sigma = 0.34$ mm. Because the bottom echo from the

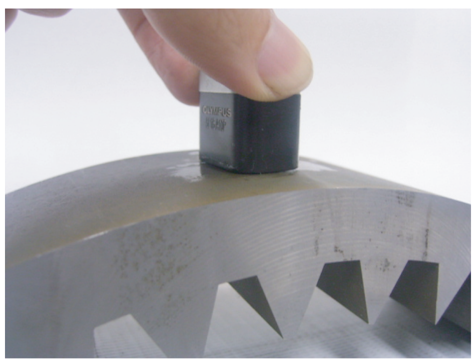
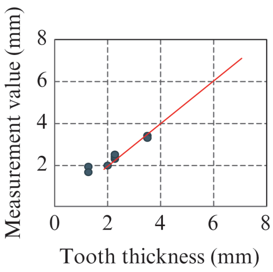
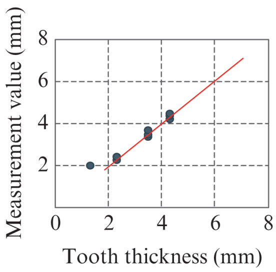
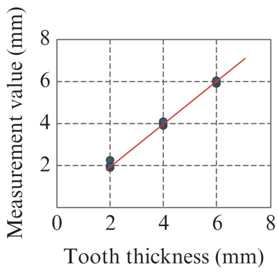


Photo 1 Flaw detection image

Table 1 Test piece measurement result

Outside diameter	Φ148	Φ282	Φ960
Module	4	6	8
Number of teeth	32	40	80
Tooth depth	Full depth tooth		Stub tooth
Pressure angle	20	20	30
Thickness of rim	14	27	164
Measurement result			
	Error of measurement 2σ=0.38 *Exclude less than 2 mm	Error of measurement 2σ=0.27 *Exclude less than 2 mm	Error of measurement 2σ=0.37 *Exclude less than 2 mm

tooth tip becomes small as wear proceeds and the thickness reaches 2 mm or less, it is possible to judge whether the tooth is on the verge of wearing out or not.

2.5 Accuracy Verification with Actual Gear Coupling

A gear coupling used in an actual machine was dismantled, and the measured values were verified against the actual wear. The results are shown in **Fig. 7**.

In this verification, actual wear was obtained by measuring the tooth thickness with a caliper, and results were compared with the results of measurements of the same positions by UT. In this figure, the x-axis shows the actual measurement values obtained with the caliper, and the y-axis shows the UT measurement results. The degree of correlation was good, at 0.9851, and measurement accuracy was 2σ = 0.51 mm. Although this accuracy was slightly lower than the above-mentioned measurement results obtained with the laboratory specimens, this is estimated to be due to the effect of the tooth shape in the actual machine.

2.6 Application to Gear Coupling Diagnosis in Actual Machines

In application of the developed method to gear coupling diagnostic work at the site, the surface of the external tooth is cleaned to a degree that enables ultrasonic testing, and full-width UT is performed in the tooth trace direction. Basically, measurement of the tooth flanks over the full circumference is not necessary, as it can be thought that similar wear will occur in any of the teeth around the full circumference. This means that evaluation is possible by measuring only several teeth. (However, all teeth must be measured if an anomaly is discovered.) This can greatly shorten inspection time. At present, the time required in inspections is approximately 30 min per gear coupling, regardless of the size of the coupling.

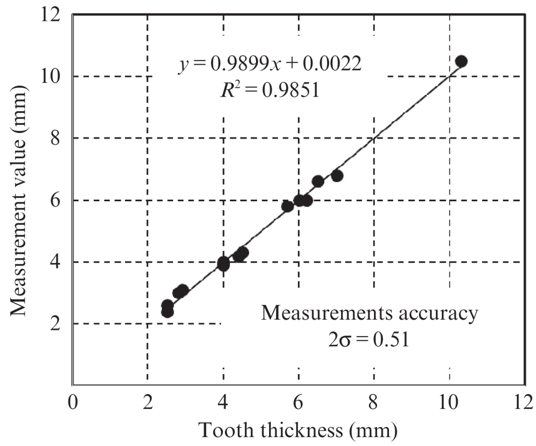


Fig. 7 Accuracy verification of the measuring equipment

3. Development of Chimney Diagnostic System

3.1 Inspections of Steel Structures

At JFE Steel West Japan Works (Fukuyama), the aerial piping corrosion diagnostic system "Scan-WALKER™" was developed in 2006 and is used in diagnosis of corrosion loss in steel structures, beginning with piping. In the development reported here, that technology was applied and further strengthened. There are restrictions on the movement of Scan-WALKER because a wired system using cables is

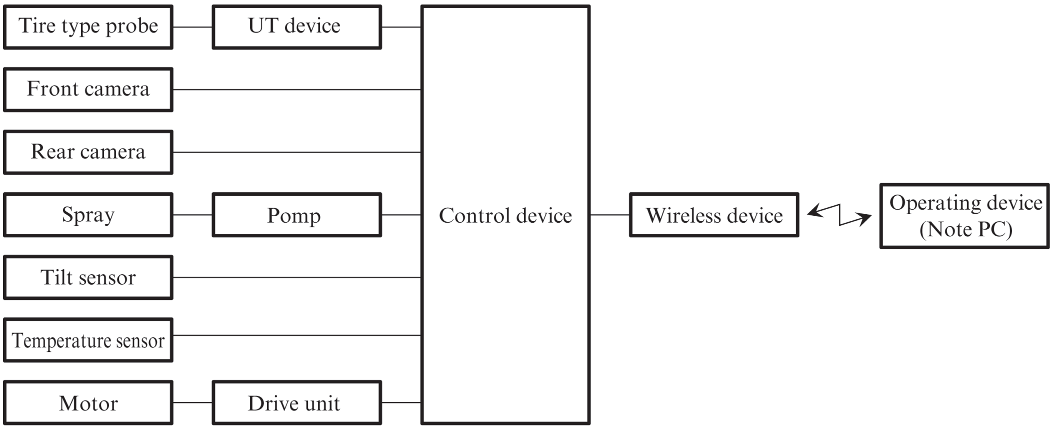


Fig. 8 Schematic diagram of chimney diagnostic equipment

adopted for both the inspection dolly and the sensors, and as a further point for improvement, the sensor section estimates the amount of corrosion by electromagnetic induction. In diagnosis of tower type structures such as chimneys, measurement must be possible from a long distance, and it must also be possible to move the measurement device freely to the desired locations on the structure and measure the material thickness there.

3.2 Main Composition of Chimney Diagnostic System

The composition of the chimney diagnostic system is shown in **Fig. 8**. The equipment mounted on the inspection dolly includes an ultrasonic testing device (tire type probe) that measures the material thickness, front and rear cameras for confirming movement from a distance, a tilt sensor that measures the tilting condition (attitude) of the device, a temperature sensor that measures the surface temperature of the chimney, a spray device that supplies the couplant to the transducer, a drive unit that drives the wheels, a control system for control of the above-mentioned equipment, and a wireless transmission device for communication with the operator. All of these devices are operated from a remote location by the operating device. A notebook type personal computer was used as the operating device in consideration of portability.

3.3 Use of Tire Type Probe

A tire type probe is used as the transducer for inspection of the surface of the steel shell of the chimney. Wear of the tire type probe can be prevented by keeping the probe tire in constant contact with the chimney surface and allowing it to rotate as the inspection dolly moves.

The structure of the tire type probe is shown in **Fig. 9**. The actual transducer element is in contact with the tire via an insertion member called a wedge. In the

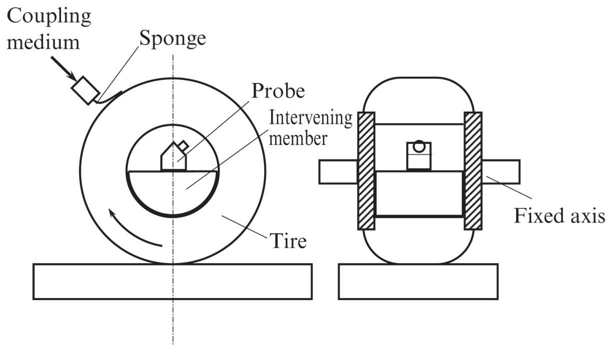


Fig. 9 Structure of tire type probe

structure of this device, only the tire rotates, and the transducer and wedge are fixed to the inspection dolly by a fixed axle and do not rotate. This makes it possible to keep the transducer in a vertical condition relative to the detection surface at all times. The tire is made of rubber, which easily adapts to the couplant, enabling measurement of the material thickness using a very small amount of couplant, which is just enough to wet the surface. This makes it possible to reduce the size of the couplant tank mounted on the inspection dolly. In conventional UT, the couplant is supplied externally by a hose, and the tank is heavy because the amount used is so large that it runs down the detection surface. In contrast, a compact, lightweight tank could be realized in the developed chimney diagnostic system because measurement is possible with only a small amount of couplant.

3.4 Drive System Using Magnetic Wheels

The drive wheels of the chimney diagnostic system are magnetized with a strong magnetic force by neodymium magnets. **Figure 10** shows the wheel structure, in which an annular neodymium magnet is positioned between two annular wheel plates to increase the magnetic attractive force. **Figure 11** shows a schematic diagram of the chimney diagnostic system as seen from

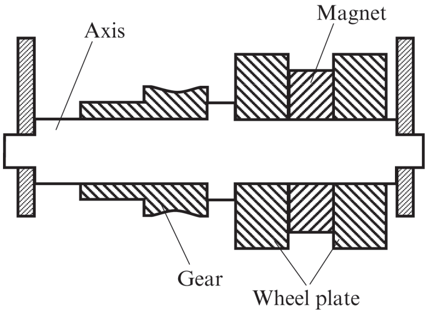


Fig. 10 Structure of magnet wheel

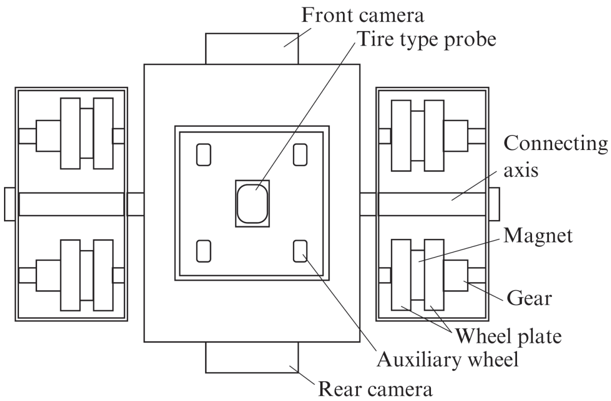


Fig. 11 Schematic diagram of a chimney diagnostic device

below. All four wheels are magnetic-wheel drive wheels. The inspection dolly drive system is divided into right and left drive units, each having two wheels. In addition to forward and reverse movement, because this structure enables separate rotation of the right and left wheels, it is also possible to turn the dolly in place by rotating the right and left wheels in opposite direction. Moreover, since wheel rotation is detected by an encoder, it is also possible to turn to the right or left while moving forward or in reverse by maintaining a difference in the rotational speeds of the right and left wheels.

Due to the extremely strong attractive force of the magnetic wheels, it is difficult to remove the device from a chimney by human strength alone. Therefore, when the device is to be removed, it is necessary to insert a rubber sheet or the like between the wheels and the chimney shell to weaken the force of magnetic attraction and allow removal.

Because the cylindrical stack shell of a chimney is assembled by welding steel plates of a certain size, weld beads inevitably exist at the joints between the plates, causing undulations in the shell surface. Difference of the level also appears due to shell thickness difference. When the chimney diagnostic system runs up and over one of these weld beads or differences in the surface level, the area of contact with the magnetic wheels decreases, and there is a danger that the inspection dolly may fall due to the loss of magnetic attractive force. For this reason, strong magnetic force is necessary in the magnetic wheels.

3.5 Attitude Control by Tilt Sensor

The tilt sensor mounted on the inspection dolly body continuously calculates the angle (vertical, horizontal, etc.) in which the inspection dolly is headed on the chimney surface, and the calculated signals are input to the control device. Although the approximate attitude can be seen because cameras for visual checks are mounted on the front and rear of the dolly, the exact angle cannot be known without this tilt sensor. Inclination values are always shown on the screen of the notebook PC used in remote operation.

By using the tilt sensor, measurements can be made while controlling the inspection dolly so as to maintain a set angle. This eliminates the need to adjust the behavior of the inspection dolly by manual operation, and enables highly accurate measurement without positional deviations.

3.6 Free Operation by Wireless Remote Control

Because control of the chimney diagnostic system is completely wireless, freedom of operation is greatly improved in comparison with the original Scan-WALKER.

In the case of wired operation, cables always follow the inspection dolly, and this causes a variety of problems. The first problem is the weight of the cables. Both a power supply cable and a communications cable are used, and the weight of these cables used increases as the travel distance becomes longer; this weight is applied to the inspection dolly. A similar problem arises if a hose is used to supply the couplant. In case a couplant such as water or oil is supplied by a hose, the hose is extremely heavy, as it is filled with couplant. As a second problem, the cables and hose obstruct the operation of the inspection dolly. If the inspection dolly moves around the circumference of the chimney, the cables and hose will be wrapped around the chimney. In this case, the cables and hose will come into contact with the steel shell of the chimney, and frictional resistance will cause tensile force in the cables and hose.

The wireless system enables free operation, as there are no cables that obstruct the movement of the inspection dolly. Continuous measurement along a spiral route is also possible by maintaining a certain angle while the dolly travels around the chimney in the circumferential direction.

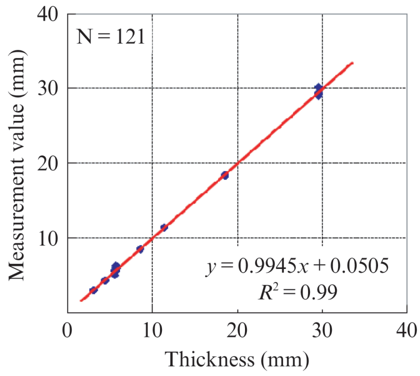


Fig. 12 Accuracy verification of the measuring equipment

Photo 2 Developed chimney diagnostic system

3.7 Accuracy Verification by Specimen Measurement

The results of measurements using specimens are shown in **Fig. 12**. The results of a total of 121 multiple repeated measurements of nine types of test specimens with different thicknesses from 3 mm to 30 mm confirmed that highly accurate measurement is possible, as the correlation value was 0.999 and measurement accuracy was $2\sigma = \pm 0.34$ mm.

3.8 Practical Chimney Diagnostic System

The developed practical chimney diagnostic system is shown in **Photo 2**. Because the travel speed of the chimney diagnostic system is approximately 1 m/min and the distance between the upper and lower decks of the chimney is about 30 m, the time required for one round-trip measurement is approximately 1 h. Since the chimney diagnostic system is driven by batteries and has a continuous operation time of 2 h when the batteries are fully charged, continuous all-day measurement is possible if multiple spare batteries are provided. To prevent inadvertent battery exhaustion, the voltage is displayed on the remote operation computer, and a warning is given if the voltage reaches the lower limit. For the amount of the couplant, 500 ml is sufficient for one day. Because the possibility of falling is a concern, a safety rope is connected to the inspection dolly from the upper deck, and action is also taken in case of unforeseen conditions.

4. Conclusion

Using ultrasonic testing (UT) technology, a diagnostic technology for gear couplings and a diagnostic system for chimney structures were developed. These technologies are used not only at JFE Steel West Japan Works (Fukuyama), but also at the company's other plants, and are making important contributions to equipment soundness evaluations and advance prevention of equipment trouble.

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