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Investigation of the On-line Monitoring Sensor for a Pipe Wall Thinning with High Accuracy

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Abstract. In Japan, the safety of nuclear power plants (NPP) has been secured by performing a time-based maintenance. However recently, NPPs were taking into consideration a new procedure using a condition-based maintenance, aiming to improve both reactors safety and operation availability. Therefore, it is needed to develop new sensors that can monitor, during reactor operation, the integrity of both piping system and pressure vessel. Also, a proper measurement method has to be chosen in order to carry out an effective on-line monitoring. In the present investigation, it was used the electromagnetic acoustic transducer (EMAT) because it does not need a couplant in a high-temperature environment (up to 200 degrees C). Based on this method, two measurements techniques have been employed using a new developed sensor, depending on the required purpose. The 1st technique is based on the Pulse Echo (PE) method. The paper analyses different methods for carrying out plates thickness measurement using EMAT and supplying a vertical ultrasonic wave. The 2nd technique is based on the electromagnetic acoustic resonance (EMAR) that is usually used for material fatigue assessment. The developed sensor measures, at 200 degrees C, a minimum 5mm±0.04mm plate thickness using PE, and 2mm±0.01mm using EMAR, respectively. Moreover, it was found no attenuation of the sensor signal even when the sensor performed a 200 hours continuously measurement.

KEYWORDS: Electromagnetic Acoustic Transducer, Pulse echo method, Electromagnetic Acoustic Resonance, pipe wall thinning, monitoring

1. Introduction

In Japan, the safety of nuclear power plants (NPP) has been secured based on a time-based maintenance. But recently, NPPs were taking into consideration new procedures using a condition-based maintenance in order to improve both reactors safety and reactors operation ratio. The measuring method of a carbon steel pipe wall thinning received lately more attention, especially after the occurrence of the pipe rupture accident in the secondary pipe system at Unit 3 of the Mihama NPP (Kansai Electric Power Co., Inc. in Japan) in August 9, 2004.

In the ruptured pipe (carbon steel) the thinning was developed after water passed the orifice of a flow-meter installed in the pipe and formed a vortex near tube wall, due to the combination of mechanical erosion caused by internal water flow and corrosion caused by chemical reaction. It was estimated that the pipe had gradually lost its thickness and that the loss of strength led to a rupture due to the internal pressure in the tube (about 1 MPa). [1]

One of the problems of the pipe wall thinning measurement is that the ultrasonic testing does not have a sensor with the durability of a non-couplant sensor which can be used in a high-temperature environment. Furthermore, due to the high cost, it is not practically feasible to attach many sensors for monitoring of wall thinning. In the past, it was shown that it is possible to have an ultrasonic inspection using a non-couplant Electromagnetic Acoustic Transducer (EMAT) [2-6]. The authors also developed in the past an EMAT for a Fast Breeder Reactor (FBR) inspection. However, there is no sensor available to measure with a high precision a wall thickness in a high temperature environment. In the present paper, it is investigated the possibility of on-line monitoring of a pipe wall thickness, using an ultrasonic sensor based of a non-couplant type. For this purpose, it was developed a low cost sensor based on EMAT.

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The sensor can be used 200 hours continuously at 200 degrees C. Even more, the sensor can measure a 10 mm carbon steel wall thickness with a ±0.1mm or more accuracy in a high temperature environment.

2. Targets

The main targets of the sensor are presented in Table 1. The targets of detection limit of the sensor were set based on the data found in the report [7]. The present study aims to obtain an accuracy higher than the detection limit of (4±0.3mm) shown in the above report.

Table 1 Development targets

Max Temp. (℃)	Durability (hours)	Limit of measurement (mm)	Accuracy (mm)	Material
200	200	≦ 4	≦ ±0.3	SS400

Regarding the sensor durability, the 200 hours was first consider as an initial target. During this time, it can be understood the variations in the thickness measurements due to modifications of the sensing property, because of the changes in the initial demagnetization with temperature of the permanent magnet. However, the durability test time is going to be extended to a two years operation time in the future.

3. Principle

3.1 Principle of ultrasonic generation

The ultrasonic wave is generated using an EMAT. The ultrasonic wave appears within a nonmagnetic material due to the vibration of material surface subjected to the Lorentz force. This force is generated on the surface of the material through the interaction of eddy currents generated by a coil and the external magnetic field produced by a permanent magnet [8-9].

However, for a magnetic material, the periodic distortion is mainly caused by the magnetostriction effect which then generates an ultrasonic wave. In the present investigation, the pipe material was made of carbon steel which exhibits ferromagnetic properties. Therefore, EMAT uses the magnetostriction effect to generate the ultrasonic wave.

3.2 Principle of magnetostriction effect type EMAT [10]

When a ferromagnetic material is subjected to a magnetic field the material changes its shape due to the reorientation of the magnetic domains, and this effect is called magnetostriction. If a time-varying magnetic field is produced by a high frequency current flowing in a coil, a ultrasonic wave will be produced on the surface of material due to the material elasticity. An electromotive force will occur in a sensing coil through the interaction of ultrasonic wave and the additional magnetic field. However, the magnetic permeability of material changes with the magnetic field intensity, and consequently the magnitude of electromotive force will also depends on the magnetic field strength.

3.3 Principle of pipe wall thinning measurement

In the paper are investigated two measurement methods. In the first one, the pipe wall thinning measurement using an ultrasonic wave is based on the Pulse Echo (PE) method. PE uses the multipath reflection of the ultrasonic wave from EMAT. The second thinning measurement uses Electromagnetic Acoustic Resonance (EMAR) method which is based on the resonance frequency of the ultrasonic oscillation.

3.3.1 Principle of the pipe wall thinning measurement using the PE method

The basic principle of the PE method is based on the arrival time of a reflected wave from the opposite side of a pipe wall. Pipe wall thinning is calculated using differential-time Δt of the reflected wave using ultrasonic velocity of the material v. A multipath reflection occurs between the upper and lower surface. Therefore, wall thinning T can be calculated using Eq.(1) [10].

$$T = \frac{v(t_{n+1} - t_n)}{2} = \frac{v\Delta t}{2} \tag{1}$$

The main characteristic of the PE method is that direct calculation of the wall thickness can be carried out using arrival time of the reflection wave. However, the PE method is not suitable for measurement of a thin wall because Δt becomes too short to measure the wall thickness.

3.3.2 Principle of the pipe wall thinning measurement using EMAR method

The basic principle of the EMAR method is based on the resonance of ultrasonic wave depending on wall thickness. The relation between n^{th} resonance frequency and wall thickness is expressed as following:

$$T = \frac{n\lambda}{2} = n\left(\frac{v}{2 f_n}\right) \tag{2}$$

where lambda λ is the wavelength. Therefore, wall thickness can be measured when ultrasonic velocity v is known. The f_n is the resonance frequency of the ultrasonic after using the Fast Fourier Transform (FFT). In this paper it is carried out a FFT of the ultrasonic reception waveform, and a resonance frequency is specified by analyzing and interpreting the frequency spectrum.

4. The trial production of a sensor

4.1 Selection of the Permanent Magnet

It is important to have a stronger magnetic flux density and a higher temperature characteristic of the magnet used for EMAT.

Although the magnetic flux density of Neodymium magnet is generally strong at room temperature, the magnetic flux density of samarium cobalt magnet has better characteristics at high temperatures, more than 200 degrees C. Therefore, it was selected the samarium cobalt magnet (®R33H, ®R28HS at Shin-Etsu Chemical Co., Ltd.). Fig.1 presents the thermal characteristics of the magnetic flux density of the samarium cobalt magnet. The graph shows the magnetic flux density up to 240 degrees C, and confirms that this magnet can be used at higher temperature.

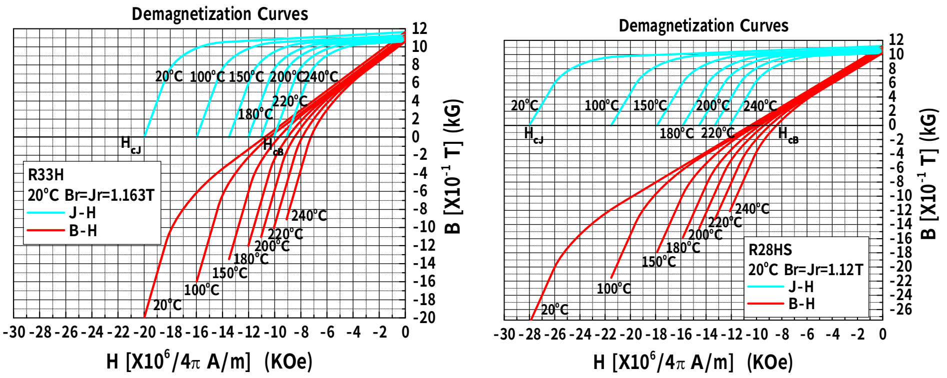

Fig. 1. The temperature characteristic of the magnetic flux density [6]

4.2 Measuring system

The measurement system of the EMAT is shown in Fig.2. The system consist of an ultrasonic oscillator, a pre-amplifier, a diplexer, an oscilloscope, and a PC for data recording.

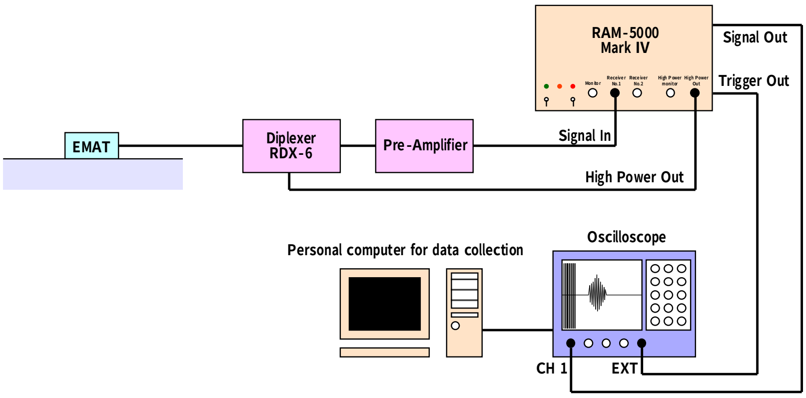

Fig. 2. Diagram of the EMAT measuring system

4.3 Manufacture of a trial sensor

Because the sensor design philosophy was to build a sensor with smaller size, higher durability and cheaper cost, a simple sensor configuration was chosen. Fig.3 and Fig.4 show the dimension and the manufactured trial EMAT.

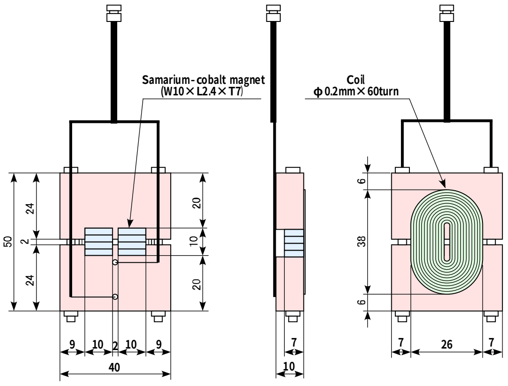

Fig. 3. Schematics of the trial EMAT structure

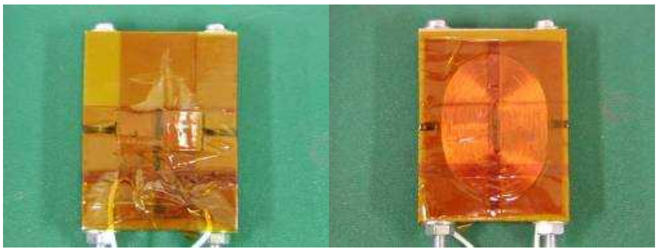

Fig.4 Photograph of trial EMAT
(left: upper side view-magnet, right: downside view -coil)

4.4 Characteristics of the EMAT transmission system

The ultrasonic wave transmitted by EMAT is a burst wave. The main characteristics of the EMAT transmission system are shown in Table 2.

Table 2 Characteristics of EMAT transmission wave

Frequency	2 MHz	Watts RMS	6400 W
Cycles per burst	2 cycles	HP Filter	1 MHz
Control	100	LP Filter	5 MHz
RF Level	3.14 V	Receiver Gain	34 dB
Bias	4.99 V	Pre-Amplifier Gain	40 dB
P-P Volts	1600 V	Sampling rate	25 MS/sec

Fig.5 shows the waveform of the transmitted burst wave with two waves. The transmitted burst wave has the strongest reflection and the shortest dead zone. Several excitation frequencies were tried, ranging from 200kHz to 10MHz, and 2MHz was chosen because 2MHz is the strongest reflective wave.

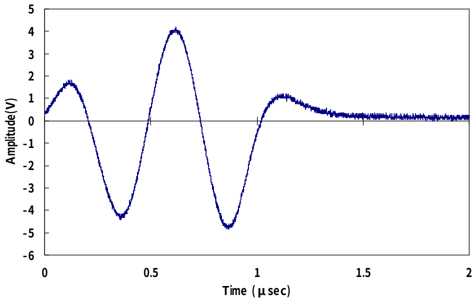

Fig. 5. Waveform of transmitted burst wave

5. The Performance Test of The EMAT

5.1 Room temperature characteristic test

The following test was performed to confirm the performance of EMAT at room temperature.

5.1.1 Test conditions

The test took place under the following conditions. The temperature is room temperature (7 degrees C). The EMAT working parameters have been described in Table 2. Specimen material is SS400 (carbon steel). Specimen sizes are 70mm×100mm×2.01, 5.01, 10.01 and 15.00mm. Thickness was measured with a micrometer (0.01mm accuracy).

5.1.2 Test result and consideration

Figures from Fig.6 to Fig.9 show waveform and results of FFT for each specimen in the 60-180 μs time interval. The waveform differential time Δt [μs] and the sound velocity v [m/s] (SS400: 3230 [m/s]) wave are used to evaluate the wall thinning T[mm]. The wall thinning is estimated using Eq.(1) for the PE method. The wall thinning is estimated using Eq.(2) for the EMAR method. PE method can measure 5mm of wall thinning with an accuracy smaller than ±0.1mm. In the case of the EMAR method, 2mm of wall thinning can be measured with an accuracy smaller than ±0.01mm.

The wall thinning test result of both PE method and EMAR method and comparison with the actual measurement are shown in Table 3 and Table 4.

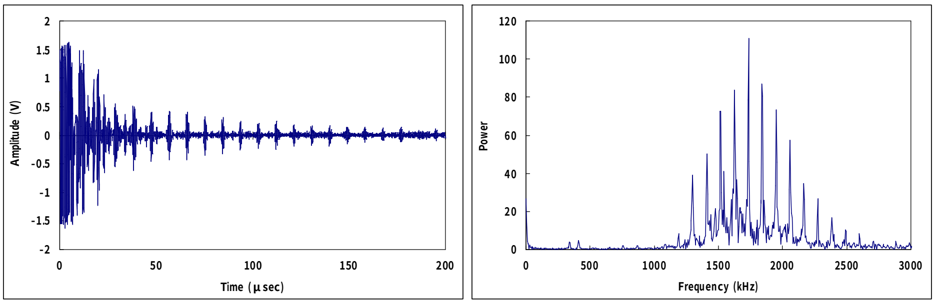

Fig.6. 15mm waveform (left: PE method, right: EMAR method)

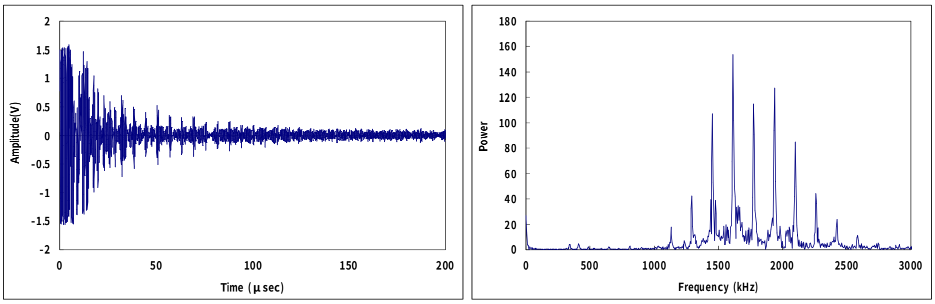

Fig.7. 10mm waveform (left: PE method, right: EMAR method)

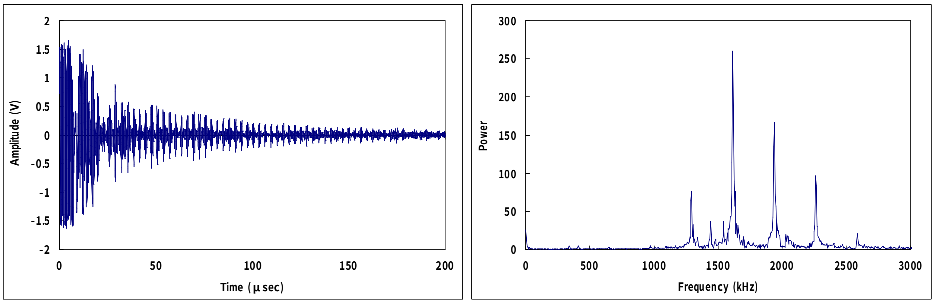

Fig.8. 5mm waveform (left: PE method, right: EMAR method)

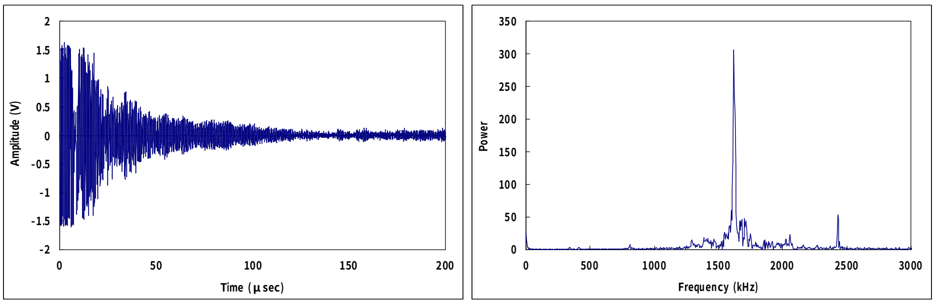

Fig.9. 2mm waveform (left: PE method, right: EMAR method)

Table 3 Result of wall thinning measurement by PE method

Material	Thinning A [mm]	Δt [μs]	Measurement Thickness B [mm]	|A-B|
SS400	2.01	-	-	-
	5.01	3.08	4.97	0.04
	10.01	6.24	10.08	0.07
	15.00	9.24	14.92	0.08

Table 4 Result of wall thinning measurement by EMAR method

Material	Thinning A [mm]	Δf [kHz]	Measurement Thickness B [mm]	|A-B|
SS400	2.01	809.7	2.00	0.01
	5.01	323.6	5.00	0.01
	10.01	161.6	10.00	0.01
	15.00	109.3	14.90	0.10

When the ultrasonic velocity is constant the frequency difference is calculated using Eq(2):

$$\Delta f_n = \frac{(n+1)v}{2T} - \frac{nv}{2T} = \frac{v}{2T} \qquad (3)$$

Therefore, a resonance frequency only depends on wall thinning and sound velocity. The theoretical value of frequency difference calculated using Eq.(3) is shown in Table3. It can be seen that the theoretical value and the experimental value were well in agreement in Fig.10.

Therefore, it was confirmed that even 2mm of wall thinning is measurable with high accuracy.

The frequency used for EMAR should be a multiple integer of the frequency in Table 5. In the examination 2MHz was used as frequency of EMAR, as it is 6 times of the optimal frequency for 5mm (323kHz), as shown in Table 5.

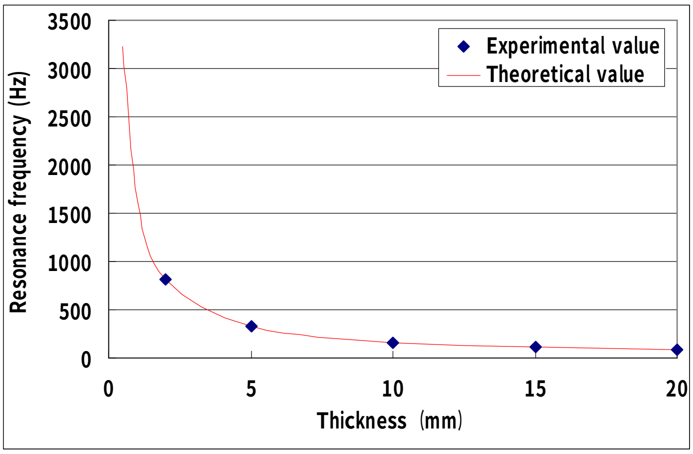

Fig.10. Relationship between the resonance frequency difference and wall thickness

Table 5 Relationship between resonance frequency and theoretical wall thickness

Thickness [mm]	⊿f [kHz]	Thickness [mm]	⊿f [kHz]
0.5	3230.0	10	161.5
1	1615.0	15	107.7
2	807.5	20	80.8
5	323.0	-	-

5.2 High temperature characteristic test

The following test was performed to confirm the performance of EMAT at high temperature.

5.2.1 Test condition

The test took place under the following conditions. Temperatures are room temp. (7 degrees C), 100, 150, 180, 200 and 250 degrees C. The EMAT working parameter has been described in Table 2. Specimen material is SS400 (carbon steel). Specimen size is 70mm×100mm×10.01mm. Thickness was measured with a micrometer (0.01mm accuracy).

5.2.2 Test result and consideration

Figures from Fig.11 to Fig.14 show the result of the high temperature test. The measurement was judged by the following two criteria. First, the signal to noise ratio is greater than two. Second, the peak separation is very clear. The reflected wave is confirmed for PE method at 150 degrees C. But it is impossible for PE method to use the reflected wave when temperature is above 180 degrees C, because the peak separation is not clear. However, it was possible to observe a frequency peak in the EMAR method, and to calculate the wall thickness at temperatures up to at least 200 degrees C. Since the sound velocity in the material at high temperature was unknown, it was extrapolated and consequently the wall thickness was calculated using data up to 150 degrees C. Fig.15 shows the relationship between reflection time and sound velocity at high temperature. This sound velocity was used in the present investigation.

The result of measured reflection time and sound velocity for wall thickness at high temperature up to 200 degrees C by PE method is shown in Table 6.The result of measured wall thickness at high temperature up to 200 degrees C by EMAR method is presented in Table 7. Using EMAR method, it was confirmed that wall thickness can be precisely measured with 0.1 mm accuracy when the temperature is bellow 200 degrees C. Furthermore, the result also shows the rightness of approximation for ultrasonic velocity. Above 180 degrees C, it also appears a resonance frequency of the magnet itself and authors consider that further optimization of EMAT structure including the magnet configuration will be required in the future.

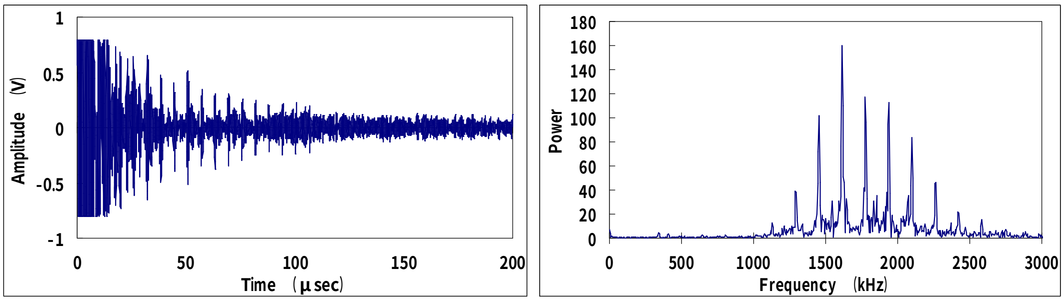

Fig.11. Room Temp. 10mm waveform (left: PE method, right: EMAR method)

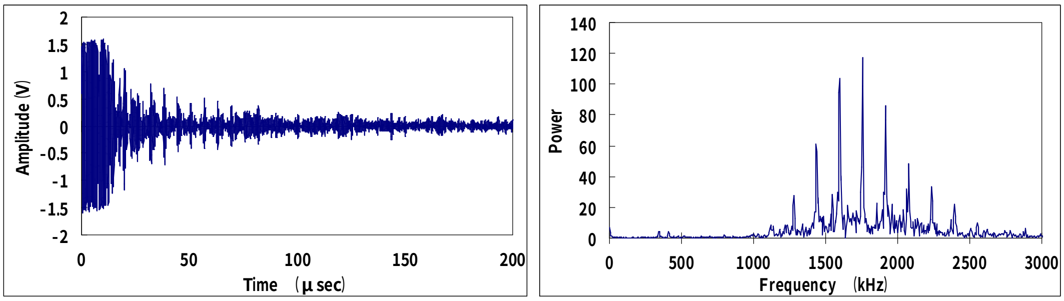

Fig.12. 100℃ 10mm waveform (left: PE method, right: EMAR method)

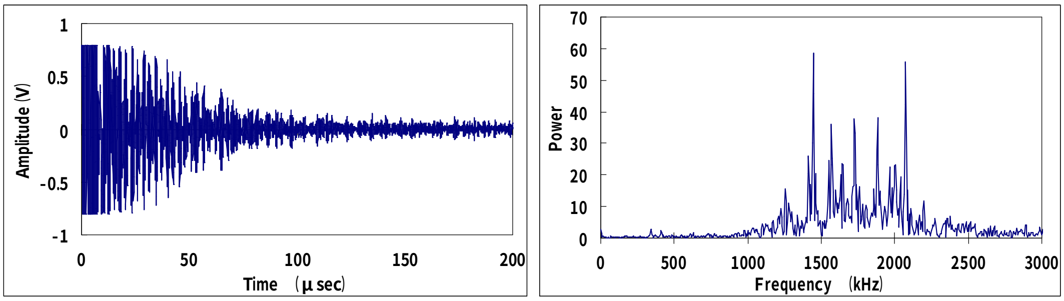

Fig.13. 200℃ 10mm waveform (left: PE method, right: EMAR method)

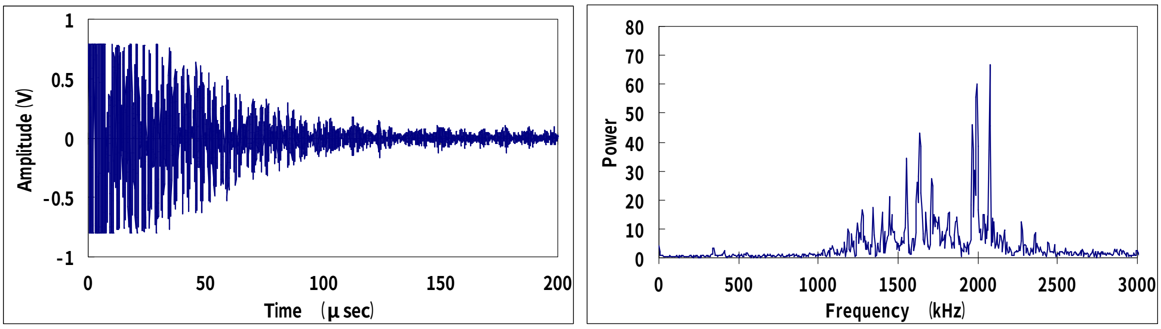

Fig.14. 250℃ 10mm waveform (left: PE method, right: EMAR method)

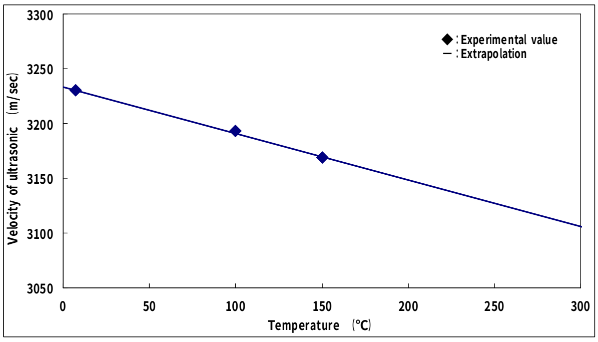

Fig. 15. Relationship between temperature and sound velocity

Table 6 Dependency of reflection time on sound velocity at high temperature

Material	Temp. [℃]	Δt [μs]	Sound velocity [m/s]
SS400	Room Temp.	6.19	3225.8
	100	6.26	3230.0
	150	6.31	3168.7
	200	-	3148.7

Table 7 Wall thickness test result using EMAR method at high temperature (A=10.01mm)

Material	Temp. [℃]	Sonic Velocity [m/s]	Peak Frequency [kHz]	Δf [kHz]	Measurement Thinning B [mm]	|A-B|
SS400	Room Temp.	3225.8	1614.4	809.7	10.00	0.01
	100	3230.0	1599.4	323.6	9.98	0.03
	150	3168.7	1584.4	161.6	10.00	0.01
	200	3148.7	1569.4	156.9	10.03	0.02

Moreover, it was investigated the reason of why ultrasonic wave was impossible to be detected by PE method above 150 degrees C. Since it was possible to detect the resonance frequency even at this high temperature, EMAT sensing proved to be suitable for monitoring purposes which requires long time monitoring at high temperatures.

5.3 Durability test at 200 degrees C

5.3.1 Test condition

The test took place under the following conditions. The temperature is 200 degrees C. The test time is 200 hours. The EMAT working parameter has been described in Table 2. Specimen material is SS400 (carbon steel). Specimen size is 70mm×100mm×10.01mm. Thickness was measured with a micrometer (0.01mm accuracy).

5.3.2 Test result and consideration

Figures from Fig.16 to Fig.17 show the results of before and after durability test at 200 degrees C. Measurement of the wall thickness by PE method is possible at 200 degrees C like the high temperature test which was mentioned in 5.2. On the other hand, wall thickness was also measured using EMAR method. By analyzing the data, it turned out that the measurement accuracy does not change at high temperature even after a continuously 200 hours operation.

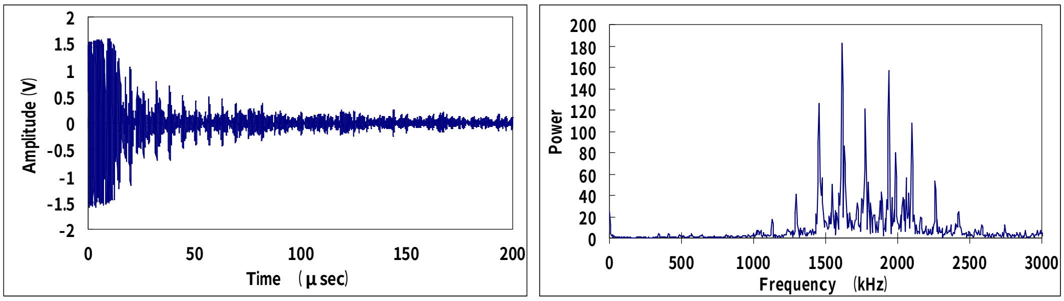

Fig.16. 10mm waveform before the increase of temperature (left: PE method, right: EMAR method)

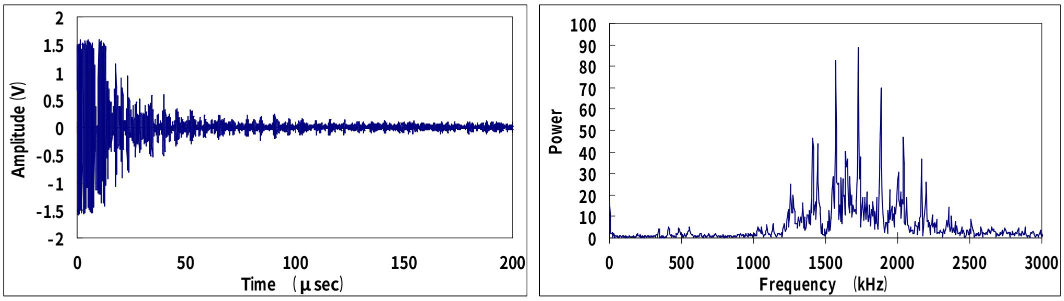

Fig.17. 10mm waveform after 197 hours temperature up (left: PE method, right: EMAR method)

The measurement wall thickness was 10.01 mm at room temperature (time=0 sec) while at high temperature it changed to a 10.03 mm.(Fig.18) By taking into account the coefficient of linear thermal expansion of iron (11.7x10-6 [mm/℃]) the wall thickness increases from 10.01 mm at room temperature to 10.03 at 200 degrees C. The measurement accuracy at room temperature is 10.00±0.01 mm. Because the wall thickness measurement at 200 degrees C was also stable (10.03 mm) it can be deducted that the measurement accuracy, considering iron thermal expansion, is about ±0.01 mm (using the high temperature velocity).

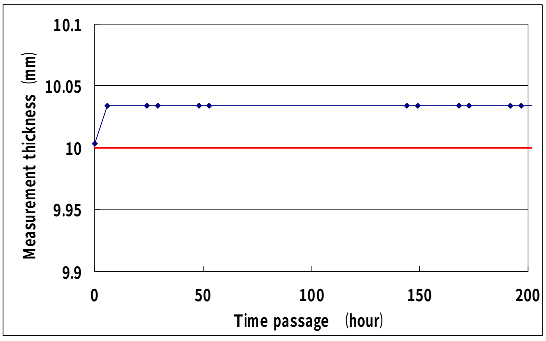

Fig.18. The wall thickness test result of continuous 200 hours operation

6. Conclusion

In the paper it was investigated a wall thickness measuring method by checking the measurement accuracy at both room and high temperatures (up to 200 degrees C). Two measurements methods were employed: the conventional PE and the EMAR method. For wall thickness up to 5mm it was checked that measurement accuracy is ±0.1 mm or less for both methods. However, a 2mm wall thickness could be measured only by EMAR. This indicated that it is possible to measure the wall thickness using two types of measuring methods but employing only one EMAT. Furthermore, a thick wall (over 5 mm) can be measured using two methods and using the same EMAT signal.

The EMAR method could be used reliable for temperatures up to 200 degrees C and it was confirmed in a 200 hours durability test.

However, in the future, will be also investigated the magnet configuration, in order to confirm whether or not after the stabilization of magnet mechanical vibrations the EMAT (for PE method) method could also be adopted for wall measurements at high temperatures.

Based on this investigation, it was also acquired the prospect of on-line monitoring of wall thickness using EMAT.

References

[1] Nuclear and Industrial Safety Agency (NISA), "Summary of the Interim Report on the Secondary System Pipe Rupture at Unit 3, Mihama Nuclear Power Plant (NPP), Kansai Electric Power Co., Inc. (KEPCO) ", http://www.nisa.meti.go.jp/text/kokusai/041022.pdf, pp.1-6, 2004

[2] R.B.Thompson, "A Model for the Electromagnetic Generation and Detection of Rayleigh and Lamb Waves", IEEE Trans. On Sonics and Ultrasonics, SU-20, pp.340-346, 1973.

[3] B.W.Maxfield, A.Kuramoto and J.K.Hulbert, "Evaluating EMAT Designs for Selected Applications", Materials Evaluation, Vol.45, pp.1166-1184, 1987.

[4] R.B.Thompson, "Physical Principles of Measurements with EMAT Transducers", in Physical Acoustics, Vol.XIX, Edited by R.N.Thurston and A.D.Pierce, New York, Academic, pp.157-181, 1990.

[5] Koorosh Mirkhani, Optimal design of EMAT transmitters, NDT&E International 37 (2004) 181-193.

[6] Yang XU, Akihiro TAGAWA, Masashi UEDA and Takuya YAMASHITA, Yusuke OHTSUKA, Kazunori OSAFUNE and Masahiro NISHIKAWA, Characterization of SH Wave Electromagnetic Acoustic Transducer (EMAT) at Elevated Temperature, in Recent Advances in Nondestructive Evaluation Techniques for Material Science and Industries, 2004 ASME/JSME Pressure Vessels and Piping Conference, PVP-Vol.484, pp.177-184, July 25th to 29th, La Jolla, San Diego, U.S.A.

[7] Japan Nuclear Energy Safety Organization, The business report concerning an examination technique in operation in advanced light water reactor safety-management technical development (High operating-ratio technology development etc.)(Phase I), pp.E-41, (in Japanese)

[8] K.Hogberg, "Ultrasonic Testing Using the EMAT Technique-Electro Magnetic Acoustic Transducer", Materials and Design, Vol.14, No.4, pp.251-252, 1993.

[9] H.J.Saltzburger, G.Hubschen and M.Kroning, "Electromagnetic Ultrasonic (EMUS) Probes: State of the Art and Developments for Application in Nuclear Power Plants", Proceedings of the 12th International Conference on NDE in the Nuclear and Pressure Vessel Industries, pp.137-142, 1993.

[10] Masahiko Hirao, Hirotsugu Ogi, EMATS for Science and Industry –Noncontacting Ultrasonic Measurements-, Kluwer Academic Publishers, 2003.

[11] The committee of an ultrasonic handbook, Ultrasonic handbook, pp.133-140 (1999).