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The Feasibility Study on a High-Temperature Application of the Magnetostrictive Transducer Employing a Thin Fe-Co Alloy Patch

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Abstract The on-line monitoring for the wall thinning in secondary system has been considered one of main issues for the safety of nuclar power plants. To establish the on-line monitoring technique for the pipe wall thinning, the development of the ultrasonic transducer working in high-temperature is very important. In this investigation, the magnetostrictive transducer is concerned for high temperature condition up to 300 ℃. The magnetostrictive transducer has many advantages such as high working temperature, durability, cost-effectiveness, and shear waves, most of all. A thin Fe-Co alloy patch whose Curie temperture is over 900 ℃ was employed as a ferromagnetic material for magnetostriction. Wave transduction experiments in various temperature were carried out and the effect of bias magnets was considered together with the dry coupling performance of the transducer. From experimental results, consequently, it was found that the magnetostrictive transducer works stable even in high temperature up to 300 ℃ and can be a promising method for the on-line monitoring of the wall thinning in nuclear power plants.

Keywords: Magnetostrictive Transducer, High Temperature, Dry Coupling, Fe-Co Alloy Patch, Shear Horizontal Wave

1. Introduction

The wall thinning of a low alloy steel pipe induced by the flow-accelerated corrosion is one of most severe problems which can occur usually in secondary piping system of nuclear power plants[1,2]. After the pipe rupture accidents causing casualties happened in Surry Unit 2 in 1986[3] and in Mihama nuclear power plant in 2004[4], the periodical and continual monitoring of the pipe thickness has been required for the healthiness of the nuclear power plants. As of today, the pipe thickness is measured by the ultrasonic testing and in-service inspection is carried out for specific and localized region during the plant overhaul. Even though there has been required more frequent inspection or on-line monitoring in plant operation, it still is not introduced to the actual field. Therefore, much attention has to be paid to the on-line monitoring of the pipe wall thinning in nuclear power plants.

For the monitoring technique of the pipe wall thickness, the development of ultrasonic transducers has to be preceded, which can be permanently installed at a pipe. Especially, the transducers should have stable and reliable performance in high temperature environment since the temperature of the secondary system typically goes up to 300 ℃ approximately.

Various methods[5-12] have been proposed for the transduction of ultrasound in high temperature condition. Lynnworth[5,9], Jen[7], Rehman[8], Prasad[11] and Kobayashi[12] used

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various types of waveguide like a clad buffer rod to measure the ultrasonic waves in a high temperature structure. Calder[6] used a pulsed laser and a laser interferometer to measured the elastic constants at elevated temperature. Kazys[10] studied about piezoelectric materials for high temperature ultrasonic transducers. Among them, the magnetostrictive transducer is expected as one of promising tools. The magnetostrictive transducer is based on magnetostriction as a working principle, the coupling effect between mechanical deformation and magnetic field. It has a strong advantage to generate and detect shear waves like bulk shear waves, torsional waves in a cylinder and shear horizontal waves in a plate[13-16]. Shear waves are very useful even for the inspection of coarse grain austenitic steel like cast iron[17,18]. Most of all, it has been considered as a monitoring sensor in high temperature since specific magnetostrictive materials have very high Curie temperature over 900 ℃[19], which means that it can operate up to that temperature. In addition, this transducer is durable and cost-effective in general.

This work concerns preliminary study on a magnetostrictive transducer for high temperature application. The main objective of this study is to check the feasibility of the magnetostrictive transducer as a monitoring sensor for the transduction of shear waves up to 300 ℃. To this end, the effects of the bias magnet and ferromagnetic material are investigated. This work employed thin Fe-Co alloy patch as a ferromagnetic material for magnetostriction[20,21]. The possibility of dry coupling between a transducer and a structure is also considered. To verify the validity of the magnetostrictive transducer, several experiments were carried out. Consequently, the results confirm that the magnetostrictive transducer works stable even in high temperature up to 300 ℃ and can be a promising method for the on-line monitoring of the wall thinning in nuclear power plants.

2. The Magnetostrictive Transducer Employing a Thin Fe-Co Alloy Patch

The magnetostrictive transducer generates and detects ultrasonic waves by the magnetostrictive effect, which denotes the deformation resulted from the magnetic domain wall motion of ferromagnetic materials under a certain external magnetic field and also the magnetic induction from the change of the dimension of ferromagnetic materials. Typically it is composed of three main components, exciting and sensing coils, bias magnets, and a magnetostrictive element bearing strong magnetostriction. Fig. 1 illustrates the schematic diagram of the magnetostrictive transducer using a magnetostrictive patch. In Fig. 1, the static bias magnetic field from the permanent magnets and the dynamic magnetic field generate shear waves of the patch since the vertical superposition of the static and dynamic magnetic field invokes shear deformation by magnetostriction.

Magnetostriction occurs in ferromagnetic materials like Fe, Ni, and Co. However, the effect of the pure material is not so much to be applied as a transducer. This work employs a Fe-Co alloy as a magnetostrictive element. This alloy has better mechanical and magnetic

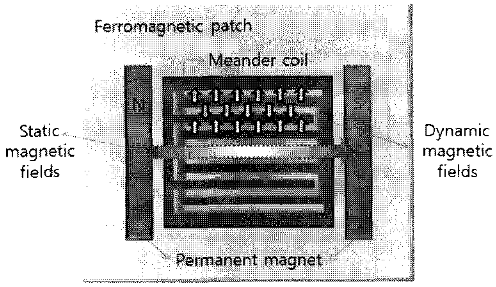


Fig. 1 The schematic diagram of a magnetostrictive transducer employing patch shaped a magnetostrictive element for shear waves

properties as a magnetostrictive element so it has been frequently applied to an ultrasonic wave transducer. The Fe-Co alloy was discovered by Preuss and Weiss in 1912 and then 50Fe-50Co (weight %), which is called Permendur, was made by Elmen in 1926. In 1932, the Fe-Co alloy with 2V (Vanadium, weight %) was made by White and Wahl. At this time, a thin plate (sheet) type of Fe-Co alloy was manufactured by cold working method. Supermendur which has the exceedingly improved magnetic characteristics was developed by Gould and Wenny in 1957. The Fe-Co alloy used in this work is more developed material with other small amount elements for magnetostriction. Table 1 shows several properties of this Fe-Co alloy. It should be carefully noted that the Curie temperature, the transit temperature from the ferromagnetic material to the paramagnetic state, is very high over 900 ℃. Therefore, it can be inferred that the magnetostrictive transducer with Fe-Co alloy can work possibly up to 300 ℃ since the magnetostrictive effect occurs below the Curie temperature.

Table 1 Material properties of a Fe-Co alloy

Magnetic Properties			
Saturation Induction		24,000 Gausses	
Maximum Permeability		10,000	
Physical Properties			
Density		8120 kg/m^3	
Specific Gravity		8.12	
Curie Temperature		940 °C	
Melting point		1724 °C	
Thermal Expansion		10.2 ppm/°C (25 to 450 °C)	
Chemistry (%)			
Iron	Balance	Cobalt	48.75
Vanadium	1.90	Niobium	0.30
Manganese	0.05	Silicon	0.05
Carbon	0.01		
Mechanical Properties			
Modulus of Elasticity		207 GPa	
Modulus of Rigidity		73 GPa	
Poisson's Ratio		0.48	

Many studies confirm the usefulness of the magnetostrictive transducer for the transduction of shear waves in room temperature but the performance of each component of the magnetostrictive transducer needs to be considered for the high-temperature application up to 300 ℃ in addition to the efficiency of the magnetostrictive element. This work focuses on two major issues; one is the bias magnets and the other is the coupling method between a transducer and a test specimen.

As for the bias magnet, the efficiency of the permanent magnet has to be concerned. A neodymium magnet is the most widely used one due to its high magnetic strength and good manufacturability, so most of the magnetostrictive transducers with permanent magnets has been using the neodymium magnet. However, in high temperature environment, the neodyminum magnet may not be suitable. Its Curie temperature is merely about 320 ℃, shown in Table 2. Therefore, the performance of the magnetostrictive transducer using neodymium magnets need to be verified up to 300 ℃. If needed, the replacement to a samarium-cobalt magnet or an alnico magnet is also considered since their Curie temperature are far higher than that of the neodymium magnet as over 700 ℃. The wave experiments were carried out to check the performance with three different kinds of permanent magnets, as shown in Fig. 2.

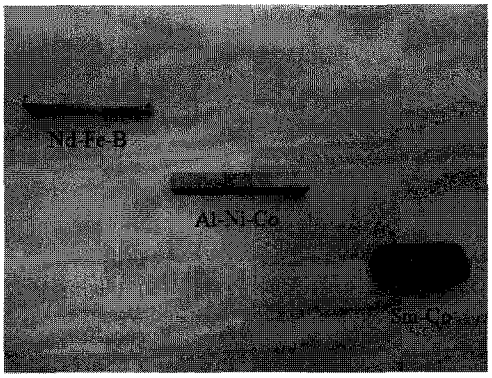


Fig. 2 A neodymium (NdFeB), a samarium-cobalt (Sm-Co), and an alnico (AlNiCo) magnet used in the experiments

Table 2 Material properties of some permanent magnets: a neodymium, a samarium-cobalt, and an alnico magnet

Property	Neodymium	Sm-Co	Alnico
Remanence, M_r (T)	1.00~1.30	0.82~1.16	0.60~1.40
Coercivity, H_c (MA/m)	0.875~1.990	0.493~1.590	0.275
Maximum energy product, BH_{max} (MJ/m^3)	0.200~0.440	0.120~0.200	0.010~0.088
Permeability	1.05	1.05	3.60
Temperature coefficient of remanence (%/K)	-0.120	-0.050~-0.030	-0.025~-0.020
Temperature coefficient of coercivity (%/K)	-0.55~-0.65	-0.15~-0.30	0.01~0.03
Curie temperature, T_c (°C)	320	700~850	850~890
Maximum permissible temperature (°C)	250	350	450~550
Density (g/cm^3)	7.3~7.5	8.0~8.5	6.9~7.3
Vickers hardness (HV)	550~650	450~600	520~630
Electrical resistivity ($\mu\Omega\cdot$cm)	110~170	86	50~75

The coupling between a transducer and a specimen is another important issue. To transmit the ultrasonic wave efficiently, the couplant is used to remove air gap. The couplant made of the refined honey is used typically to transmit shear waves but the liquid-type couplant cannot be used in high temperature condition since water in couplant turns into vapor. As one of alternatives, the epoxy adhesive also causes inconvenience due to troublesome process, long cure time, and cleaning up after testing. Most desirable is the dry coupling without any couplant. Therefore, this work also carried out experiments to check the effect of the dry coupling.

3. Wave Experiments in High Temperature Condition with Various Bias Magnets

To confirm the performance of the magnetostrictive transducer in high temperature condition, some experiments to measure shear waves were carried out in various temperatures.

Fig. 3 shows the experimental setup for the high temperature wave experiments. Two magnetostrictive transducers are installed on the Fe-Co alloy patch; one for transmitting and the other for receiving. Each transducer has two bias permanent magnets and the distance between the transducers is 50 mm. The Fe-Co alloy patch was attached on the hot plate (HSD 180), which can supply heat up to the maximum 380 °C. A ceramic glue (BD-3000) was used to bond the patch to the hot plate. The thickness of the Fe-Co alloy patch is 0.15 mm. Thin meander lines patterned coils made by the printed circuit board manufacturing process were used as an exciting and sensing coils.

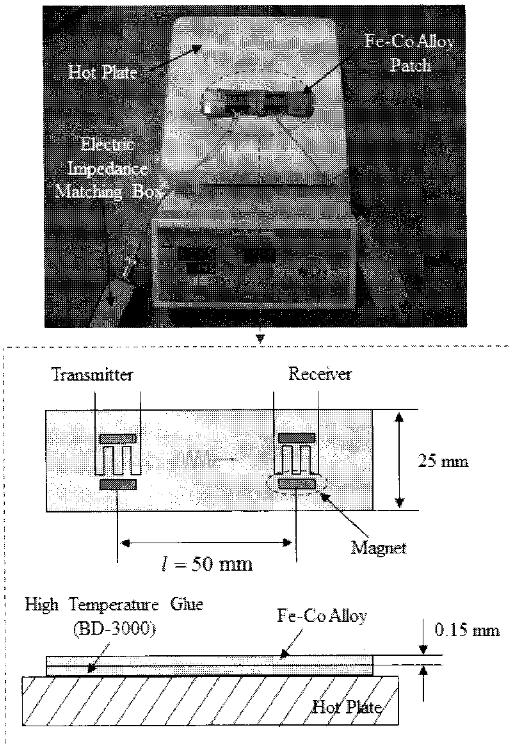


Fig. 3 The experimental setup for the shear wave measurement with magnetostrictive transducers in high temperature condition

To monitor the temperature of the patch, its surface temperature was measured with the thermometer at the center of the patch between two transducers. Fig. 4 shows the infrared thermometer used in this experiments. The magnitude of the electrical impedance of the meander coil increases gradually as the temperature rises but the amount of the change is negligible as merely 0.04 Ω (0.28 %).

Fig. 5 shows the schematic diagram of the experimental arrangement for the exciting pulse driving and the measured signal receiving. As an excitation signal, one cycle sinusoidal pulse was supplied by the ultrasonic pulser (RITEC RAM-10000).

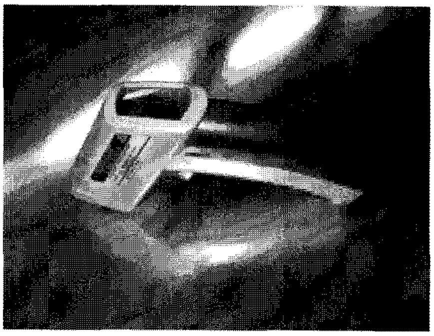


Fig. 4 The infrared thermometer (-30°C~500 °C)

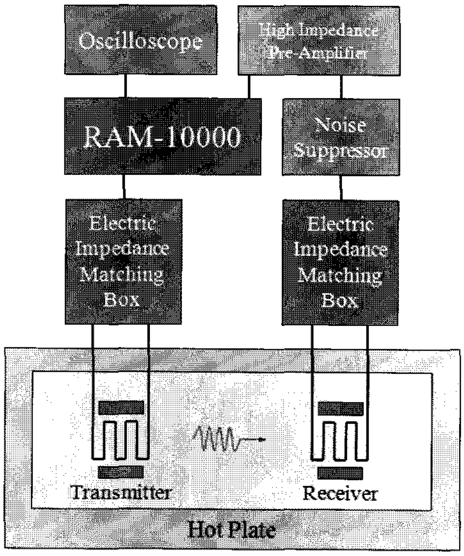
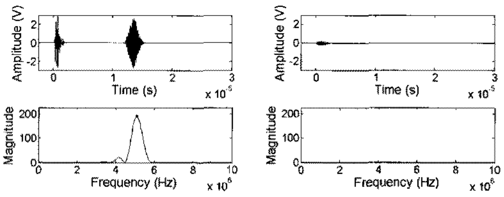


Fig. 5 The schematic diagram of the experiment for wave propagation in high temperature condition

The frequency of the generated wave was set to be 5 MHz. For this frequency (f), the line distance ($d=\lambda/2$) of each meander coil is 0.6 mm since the shear wave propagates with the wave velocity (c) about 3000 m/s, which is calculated by the relation $c=f\lambda=f2d$.

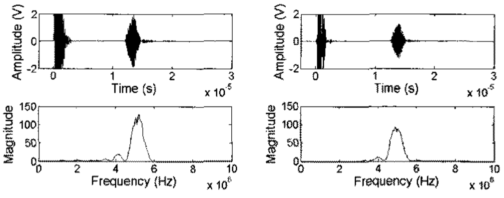
As changing the bias magnets, the shear wave measurement experiment was carried out in various temperature. Fig. 6 shows the measured signals at room temperature and high temperature near about 300 ℃, when the temperature is the measured value at the upper surface of the center of the patch. The measured signals show that the measurement performance in room temperature is similar with any permanent magnets. In high temperature, however, the wave was hardly measured with the neodymium magnets unlike the cases with the samarium-cobalt and the alnico magnets.

< Neodymium magnet (Nd-Fe-B) >



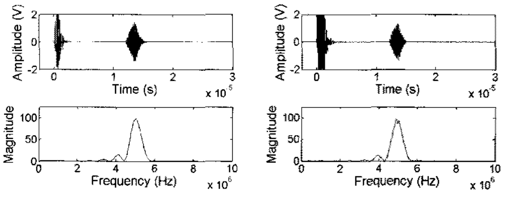
(a) 29.4 °C (b) 246.4 °C

< Samarium-Cobalt magnet (Sm-Co) >



(a) 30.4 °C (b) 301.6 °C

< Alnico magnet (Al-Ni-Co) >



(a) 26.2 °C (b) 302.8 °C

Fig. 6 The measured signals at room and high temperature near 300℃ and their Fourier transform

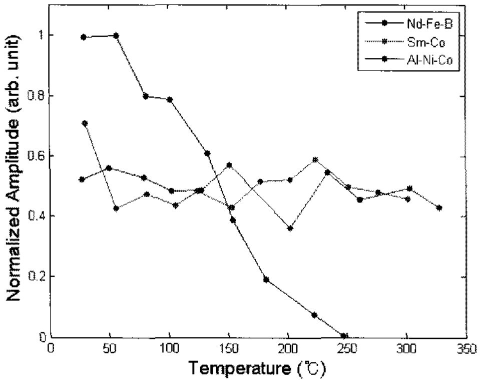


Fig. 7 The peak-to-peak amplitude of the measured shear wave signals in various temperatures. Each amplitude is normalized to the amplitude of the case with the neodymium magnets in room temperature.

Fig. 7 shows the amplitude of the measured wave. In case of employing the neodymium magnet, the measured signal decreased very steeply with the temperature rising. At 150 °C, the amplitude reduced to about half in room temperature. At 250 °C, the wave was hardly measured. However, other cases with the samarium-cobalt and the alnico magnets show stable signal amplitude with the temperature changing. From the results, several considerations have been found that the magnetostriction characteristics of the Fe-Co alloy patch is stable and the magnets are major concerns for the magnetostrictive transducer up to 300 °C.

4. Experiments for the Effect of Coupling

To check the dry coupling efficiency, wave experiments were carried out. Fig. 8 shows the photograph of the experiments for the generation and detection of shear horizontal guided waves in a carbon steel plate. The same experimental arrangement in Fig. 5 was applied except that the modular type transducer was used. The transducers were made to generate and measure the shear horizontal wave at 281 kHz. The distance (l_d) between the transmitting and receiving transducers was 500 mm. The thickness of the test plate was 12 mm.

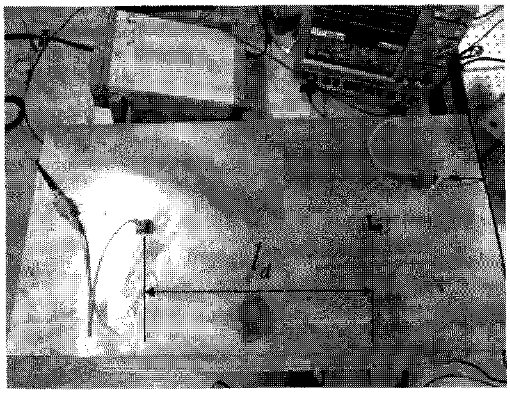
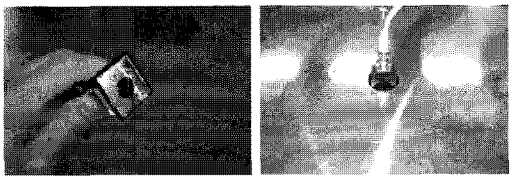
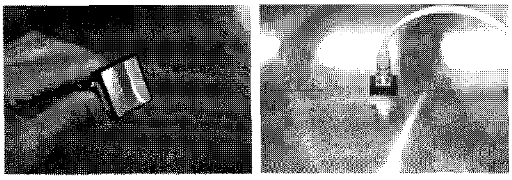


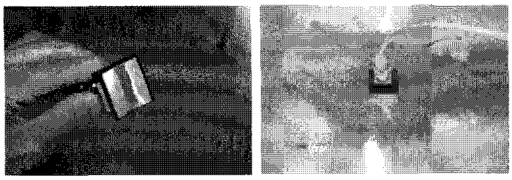
Fig. 8 The generation and detection of SH guided waves to check the coupling effect of the magnetostrictive transducer.



(a) Shear gel couplant



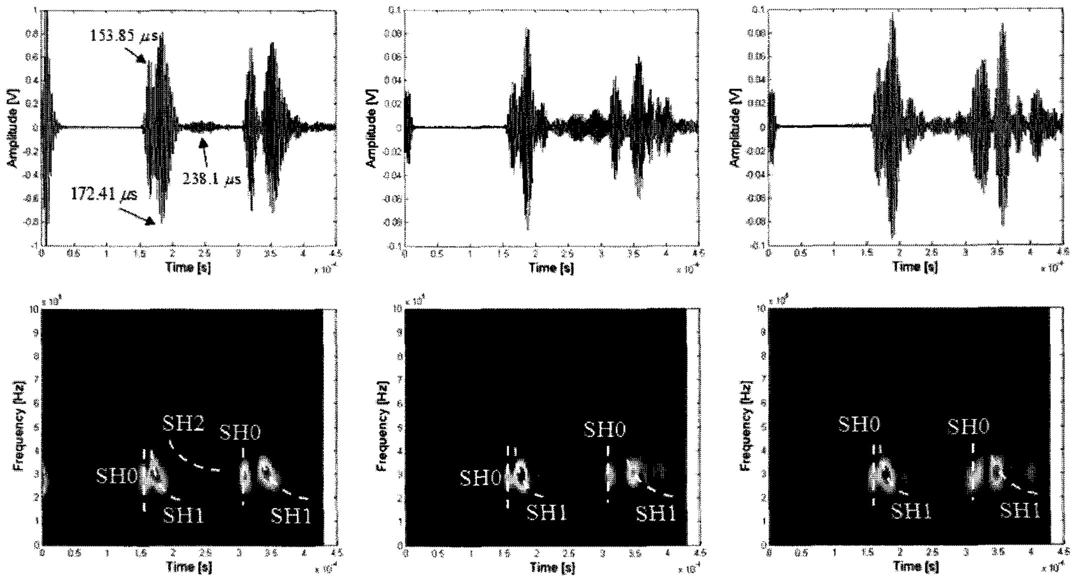
(b) Dry coupling



(c) Dry coupling with surface polishing

Fig. 9 Various coupling methods for the magnetostrictive transducer

Three case experiments shown in Fig. 9 were conducted; using the shear couplant (Sonotech), no couplant (dry coupling) without preprocess, and no coupling with the surface polishing. For the last case, the test specimen was smoothly polished by a grinding machine.



(a) Shear gel coupling (b) Dry coupling (c) Dry coupling with surface polishing

Fig. 10 The measured signal and its spectrogram of SH waves of 281 kHz

Fig. 10 shows the measured wave signals and their spectrograms by the short-time Fourier transform (STFT) with each coupling method. As shown in the time-frequency analysis by STFT, fundamental (SH0) and second shear horizontal wave mode (SH1) were measured. In case of the dry coupling, the magnitude of the measured signal decreased remarkably by about 10 times of the case with the shear couplant. However, the signal to noise ratio maintained very enough to detect shear horizontal waves. Especially, the wave mode from the time-frequency analysis in Fig. 10 can be identified very similar with each cases. From the results, it can be concluded that the magnetostrictive transducer can be valid to generate and detect waves even with the dry coupling.

In this experiments, the effect of the polishing hardly appeared, which seems to be resulted from the wavelength is relatively large as long as the surface condition does not affect the transmission at the boundary between the transducer and the specimen. If the frequency is higher and the wavelength is shorter, then the effect of the surface condition is expected to increase.

In conclusion, overall assessment of the dry coupling for the magnetostrictive transducer is quite affirmative. It can be sure that the dry coupling capability makes the magnetostrictive transducer more possible to be applied in high temperature environment.

5. Conclusion

The feasibility study of the magnetostrictive transducer (MsT) employing a thin Fe-Co alloy patch for a high-temperature application was conducted up to 300 °C. The effect of the bias magnets and the dry coupling were considered. From experimental study, it has been found that the magnetostrictive transducer can be a promising tool for high temperature ultrasonic testing since it shows stable and reliable performance with suitable choice of bias magnets and the dry coupling testing is also possible.

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