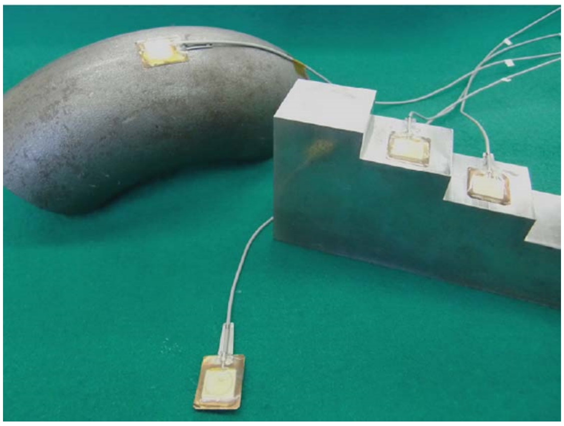
Technology of Flexible Thin-film Ultrasonic testing Sensor with High Temperature Resistance



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Mitsubishi Heavy Industries, Ltd. (MHI) has developed a thin-film ultrasonic testing (UT) sensor, which is thin, flexible and usable at high temperatures. The thin-film UT sensor can be used for continuous monitoring during operation or as an alternative to a conventional UT sensor in measuring the thickness of plant piping and vessel. This paper describes our thin-film UT sensor in terms of its characteristics and performance, research for usability expansion and application in the inspection of actual units.

1. Introduction

In power plants, pipe wall thinning due to flow-accelerated corrosion or liquid droplet impingement erosion is commonly known. For the realization of better facility safety, it is important to improve the technology for wall thinning monitoring. Within a predetermined period of regular plant inspection, an enormous number of thickness measurements are carried out at many plants in accordance with guidelines and standards. In many of these procedures, however, sensors have to be attached by hand at each measurement location. Such manual measurement of thickness involves the following challenges:

(1) When measuring thickness, there is a concern that the measurement accuracy may be affected, because the measurement location or physical contact state between the sensor and the object to be measured can slightly vary with every measurement.
(2) For every measurement, additional work is required (e.g., removal/re-installation of heat insulating materials and assembly/disassembly of scaffolding).
(3) With measurement in every regular inspections, it may not be possible to keep up with changes in the wall thinning which take place within a short period.

To solve these issues and make the sensor applicable to the technology for monitoring wall thinning tendencies during the system operation and thickness measurement in after-sales services, we have developed a thin-film UT sensor that is both thin and flexible and has superior heat resistance.

2. Characteristics/application of the thin-film UT sensor

Figure 1 shows the configuration of the thin-film UT sensor and a comparison between the thin-film UT sensor and a conventional UT sensor.

The thin-film UT sensor consists of the bottom electrode, piezoceramic film, top electrode and signal cables. This flexible sensor is less than 1.0 mm in thickness and can be closely attached in accordance with the curved surface of objects such as piping. As the thin-film UT sensor is only

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made of metals and ceramics, its durability in high temperature environments is superior to the conventional one containing damping materials such as resin. Materials such as lead zirconate titanate (PZT) and lithium niobate ($LiNbO_3$) are used for piezoceramic films (i.e. functional ceramics). It is possible to produce a thin-film UT sensor that is suitable for the applied temperature range.

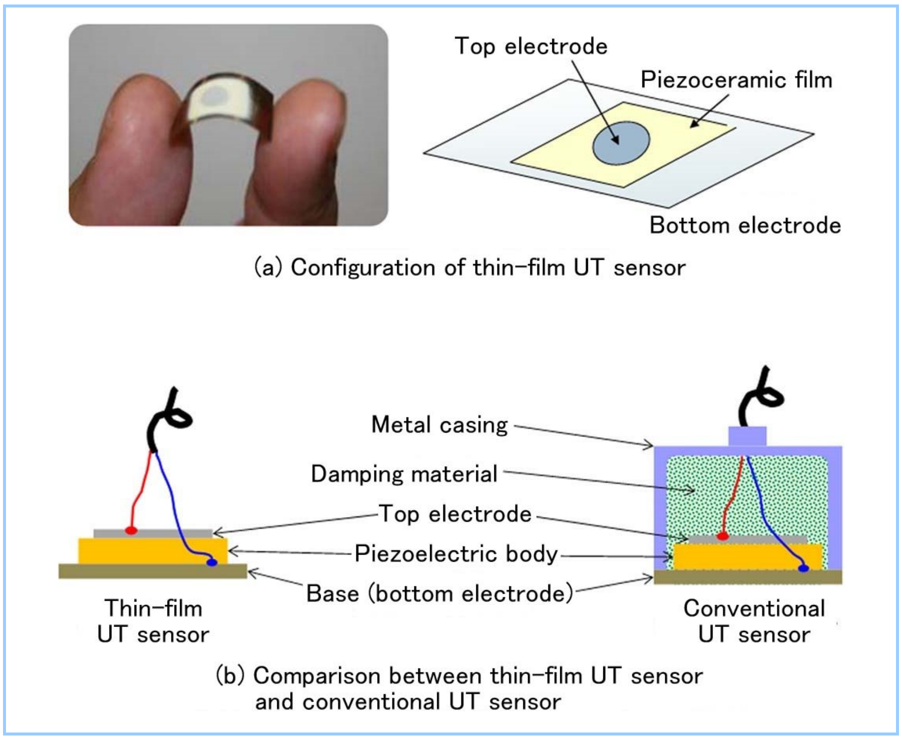

Figure 1 Configuration of thin-film UT sensor and comparison between thin-film UT sensor and conventional UT sensor.

There are three possible major applications of thickness measurement using the thin-film UT sensor.

The first application is a substitute for manual measurement of thickness in regular inspections with appointed locations for measurement. As the thin-film UT sensor is thin and heat resistant, it can be left attached to high temperature pipes during plant operation. Therefore, it is expected that the measured value variations arising from differences in the measurement location and the state of physical contact with the object to be measured will be eliminated. Furthermore, because the thin-film UT sensor can be left attached, there is no need for additional work such as the removal/re-installation of heat insulating materials and the assembly/disassembly of scaffolding, consequently reducing the cost and inspection period.

Secondly, as the thin-film UT sensor can be left attached to the piping, it can be used to continuously measure and monitor thickness during plant operation. Such monitoring using the thin-film UT sensor can indicate how altered operating conditions or water quality can affect the rate of wall thinning. Thus, while checking the effect of alterations, the operating conditions and water quality can be adjusted for optimization from the perspective of wall thinning prevention. **Figure 2** is a conceptual diagram of such adjustment through the monitoring of wall thinning tendencies.

Thirdly, because of its flexibility, the thin-film UT sensor can be applied to the curved contours of objects such as piping and vessel. A conventional UT sensor has difficulty in stably fitting on the curved surface of a structure with a large curvature such as the crotch of a T-joint pipe or small-bore piping, because it is enclosed in a metal casing as illustrated in Figure 1 (b). On the other hand, as the thin-film UT sensor is flexible, it can be bent in accordance with the contours of the object to which the sensor should be attached. The stable measurement of thickness is thus enabled.

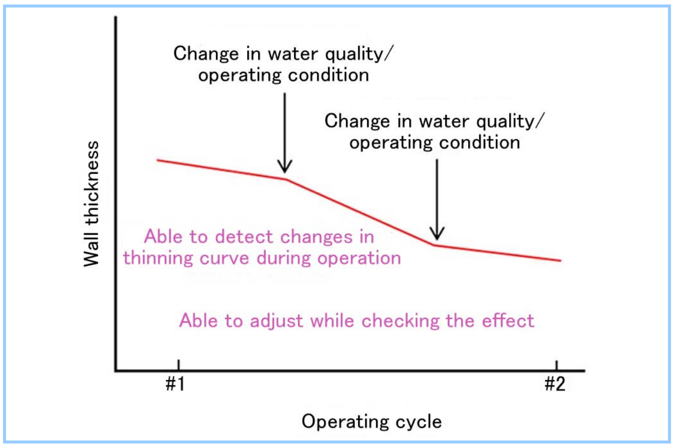

Figure 2 Conceptual diagram of the adjustment of operating conditions and water quality by monitoring of wall thinning tendencies.

3. Performance of the thin-film UT sensor

This chapter addresses the performance of the thin-film UT sensor. Firstly, we will present the verification results on the accuracy of thickness measurement when the surface to be examined is curved. As a comparison, a pencil-type UT sensor (oscillator size: φ 3 mm) that is commercially available for special purposes was used to measure the thickness of the crotch of a T-joint pipe and the inner curvature of an elbow with a piping size of 20A or above (outer diameter: 25-61 mm). The obtained results were compared with those of the thin-film UT sensor to verify its accuracy in the thickness measurement of curved structures. **Table 1** gives the specifications of the pipes used in the testing.

Table 1 Specifications of pipes used in thickness measurement accuracy test of curved structures

Type		B	Outer diameter (mm)	Sch
A	Elbow inner curvature	3/4	27.2	S80
B	Crotch	3/4	27.2	S40
C	Crotch	1	34	S40
D	Crotch	3/4	27.2	S80
E	Crotch	1	34	S80
F	Crotch	2	60.5	S160

As shown in **Figure 3**, the maximum difference between the values obtained by these two sensors is 0.1 mm or smaller, which indicates that thickness measurement using the thin-film UT sensor is as accurate as the pencil-type UT sensor. The pencil-type UT sensor has an edged tip like a pencil and therefore is point-contacted with the curved surface of the object to be examined, which makes stable measurement difficult. On the other hand, the thin-film UT sensor is flexible and has a surface of its own to be attached in accordance with the curved surface of an object, enabling stable measurement to be conducted.

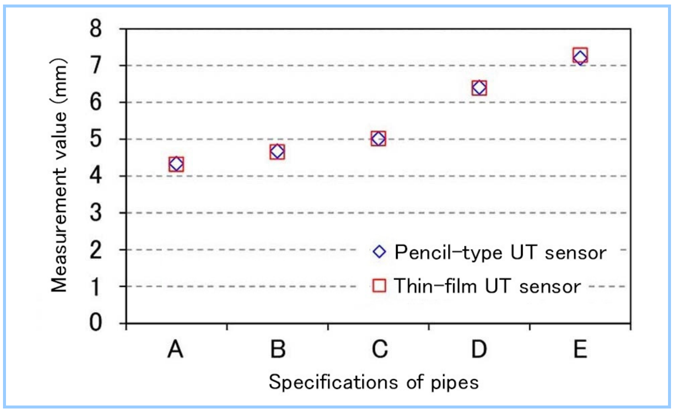

Figure 3 Comparison of measurement with thin-film vs. pencil-type UT sensor

Presented next are the results of the heating test, which was conducted to verify the high-temperature durability of the thin-film UT sensor. **Table 2** shows the details of the testing such as the type of thin-film UT sensor. To verify the thin-film UT sensor's capability of the stable measurement of thickness in high temperature environments, the sensor was fixed on a piece of piping material and was placed in an electric furnace for heating. The obtained signal waveforms and data on thickness was examined. First, we conducted the thermal cycling test in which the two levels of temperature were repeated alternately: room temperature and high temperature (200°C or 300°C). According to the results, the difference in thermal expansion between these two temperature levels did not cause the thin-film UT sensor to become detached. It has been demonstrated that the thickness measurement after the 10th thermal cycle can attain the same accuracy as the 1st cycle.

Table 2 Conditions of high-temperature durability test on thin-film UT sensors

Heating temperature (°C)	Type of piezoelectric body	Total heating period (maximum) (days)
200	PZT	916
300	PZT	521
	BiT	1064
	$LiNbO_3$	88

PZT: Lead zirconate titanate, BiT: bismuth titanate, LiNbO3: lithium niobate

Figure 4 shows the signal waveforms at room temperature and high temperature obtained in the thermal cycling test. Conducted next was a continuous heating test. A test body on which the thin-film UT sensor was fixed was continuously heated at a constant temperature, to obtain signal waveforms and thickness data on a regular basis.

The results show no indications of sensor deterioration such as the rapid attenuation of signal sensitivity, the production of significant levels of noise and the distortion of waveforms (**Figure 5**), which confirms the continuation of the stable measurement of thickness for at least 2 years. During this testing period, the temperature decreased several times because of power failures, but did not cause any changes in signals. The continuous heating test will be continued to collect more data.

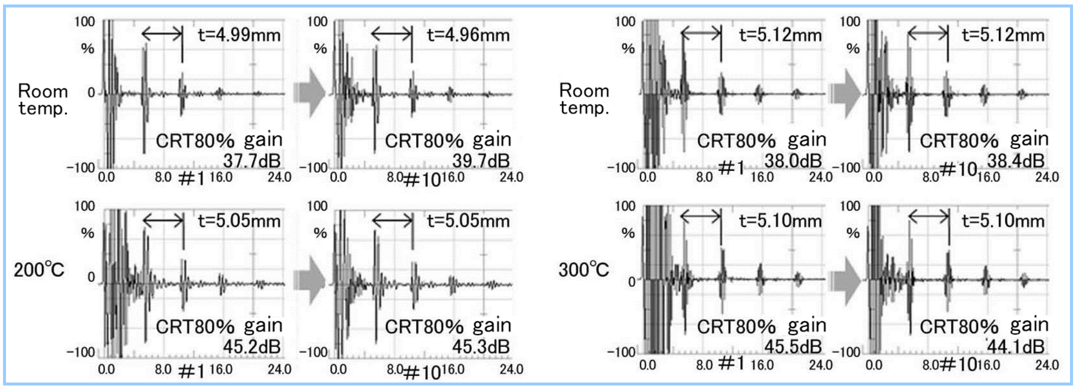

Figure 4 Signal waveforms at room temperature/high temperature in thermal cycling test

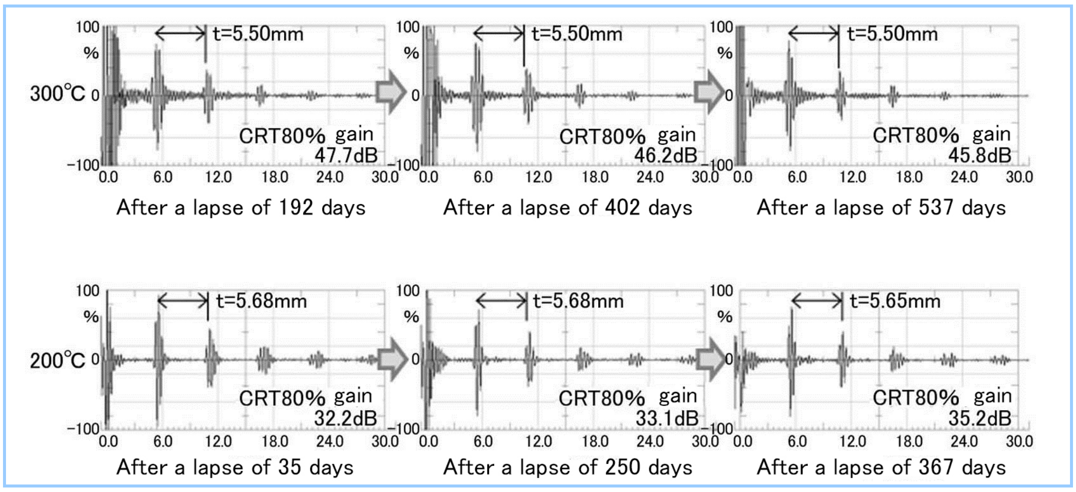

Figure 5 Results of wall thickness measurement on test piece (piping material) with thin-film UT senor affixed

4. Development of the thin-film array sensor

To apply the thin-film UT sensor to crack inspection, we have developed a thin-film array sensor that can be used as a phased array (PA) sensor. As shown in **Figure 6**, the top electrode formed on the piezoceramic film is segmented to allow the piezoceramic film directly beneath each segment of the top electrode to function as an individual piezoelectric element.

To verify the flaw detection performance, a thin-film array sensor with the top electrode consisting of eight segments (i.e., 8 channels) was made as a test sensor and an 80-mm thick aluminum block with side drill holes was used as a test body. As a comparison, commercially-available PA sensors were used under the same condition as the thin-film array sensor (which means that only 8 channels of piezoelectric elements are allowed to use for producing a flaw waveform). **Figure 7** gives the photographs of testing and the obtained flaw detection sensor images. As shown in the figure, the thin-film array sensor has the ability of detecting all the defects (side drill holes) as with the case of commercially-available PA sensors.

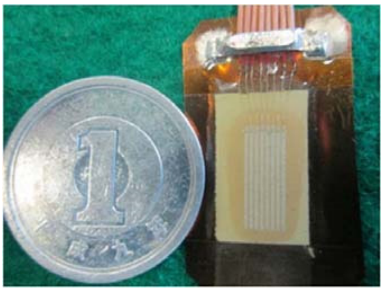

Figure 6 Thin-film array sensor

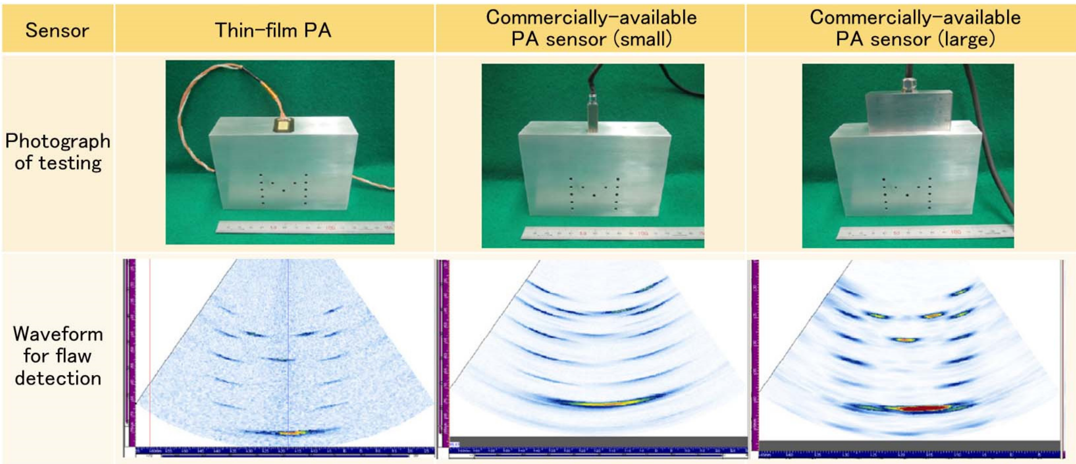

Figure 7 Flaw detection by thin-film array sensor

Explained next are the results of fatigue crack detection by the thin-film array sensor. An initial crack was introduced into a carbon steel test piece with a thickness of 22 mm. With the fatigue testing machine, we let the crack grow and monitored the tip of the crack using the thin-film array sensor. As shown in **Figure 8**, flaw corner echoes and tip echoes showing the tip of the crack were detected in the course of the crack reaching nearly 10 mm in length (50% of the thickness).

To assess the sizing accuracy of crack depth, we conducted flaw detection by the thin-film array sensor using a test piece with an EDM (electric discharge machining) slit for which the exact depth is known, and compared the obtained value with the given depth of the slit. According to the results, the error between the value obtained by the thin-film array sensor and the depth of the EDM slit fell in the range of 5%t, thus demonstrating satisfactory applicability to the inspection of actual units. **Figure 9** shows the results of flaw detection accuracy testing.

Based on the above verification results on the performance of the thin-film array sensor, we will develop a multichannel thin-film array sensor with an increased number of channels and improve the sensitivity of the piezoelectric film to make our thin-film array sensor applicable to the inspection of actual units.

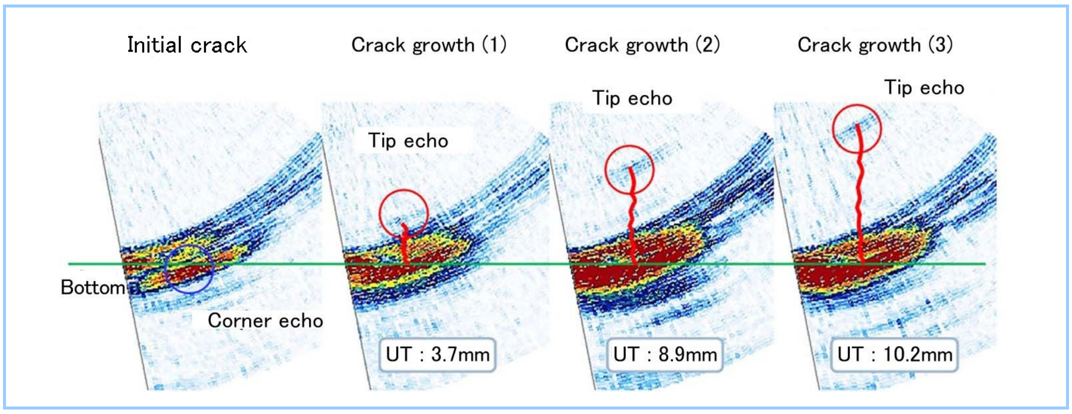

Figure 8　Fatigue crack growth detected by thin-film array sensor

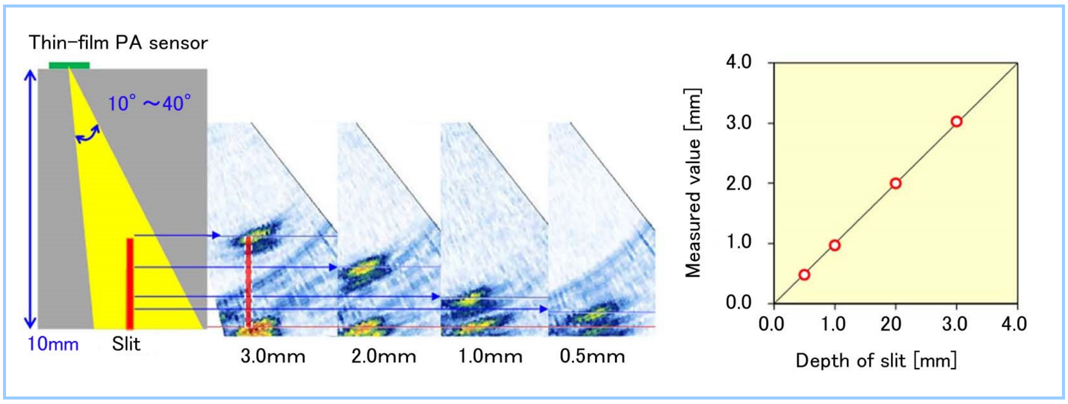

Figure 9　Results of flaw detection accuracy tests

5. Application in the inspection of actual units

This chapter deals with the application of the thin-film UT sensor in the inspection of actual units. For the applicability evaluation and the identification of problems that can be caused under actual operating conditions, a thin-film UT sensor was attached to the piping (with a temperature of ≤200°C) of a power plant in Japan, and the thickness measurement was carried out over nearly a year as an actual unit trial (the trial is still ongoing). The obtained signal waveforms show no indications of deteriorating tendency such as the rapid attenuation of signal sensitivity, the production of significant levels of noise and the distortion of waveforms, which confirms the continuation of the stable thickness measurement.

As the next step, we are planning a trial in higher temperature environments, for which it is required to devise a more suitable sensor fixation method, etc. The necessary research and development are under way.

6. Conclusion

As one of the non-destructive inspection technologies to verify the soundness of structural components such as piping and vessel and realize secure and safe operation, we are developing a technique for thickness measurement using the thin-film UT sensor. As the sensor is thin and flexible, it can be bent in accordance with the curved contours of the object to be measured. The sensor is also characterized by its superior high-temperature durability because it is only made of ceramics and metals. We have established the manufacturing technology for the thin-film UT sensor, covering the whole manufacturing process starting from the formation of ceramic film until the attachment of signal cables, and the assessment/analysis based on the obtained signal waveforms. It is therefore possible to customize the thin-film UT sensor according to the requirements for a specific application of the sensor (e.g., size, contours and temperature condition). The performance of the thin-film UT sensor was verified by comparing its thickness measurement accuracy and long-term heat resistance (through the heating test) with the results of the conventional sensor. Some grounds for application in an actual environment were obtained. As applied research, a thin-film array sensor is currently under development with the view to use of the sensor for not only thickness measurement, but also crack sizing, thereby expanding the applicable range of thin-film UT sensors.

For application to actual units, we have proceeded with trials under actual operating conditions. Some grounds for applicability in a 200°C environment were obtained. We will improve sensor fixation method etc. to make our sensor applicable in even higher temperature environments.

While working on issues such as the establishment of an installation method of the thin-film UT sensor in high temperature environments and the realization of mass production, we would like to offer solutions with functionality such as appropriate proposals for maintenance and repair, the construction of a chronological database and measurement data processing software as part of a wall thinning monitoring system using the thin-film UT sensor.

We will carry on research/development for high-temperature environment applications and establish a mass production system. A remote monitoring system which integrates the thin-film UT sensor with wireless communication technology will be developed, and by further combining it with an appropriate maintenance plan, we will create/offer new customer values.

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