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New Inspection Technology for Steel Products

MATSUI Yutaka[*1] UCHITOMI Noriaki[*2] TATE Masami[*3]

Abstract:

In order to prevent products with flaws being shipped out of the plant, JFE Steel has developed new quality assurance technologies. A new automatic ultrasonic tester using the phased array UT has been installed at a pipe mill to achieve more reliable flaw detection in the welded part of LSAW pipes. It combines a matrix phased array UT with the direct incidence method in order to detect incomplete penetration defects at the center of a weld with high S/N ratio and good repeatability. For inspection of flaws on the plate surface, twin-illumination and subtraction technique has been developed. This makes it possible to detect dented flaws on the plate surface by canceling disturbances due to surface patterns. An automatic detector equipped with this technique has been applied to a plate mill in JFE Steel.

1. Introduction

Quality inspection technologies are indispensable for manufacturing and supplying high quality products to the market. Highly reliable quality inspection technologies make it possible to improve manufacturing conditions, and also prevent shipment of products with defects (flaws) to the market. Because JFE Steel conducts a diverse range of inspections in the manufacturing processes for pipe products and plate products, including various types of ultrasonic inspection, X-ray inspection, magnetic particle inspection and dimensional measurement, the company has positioned these quality inspection technologies as critical technologies and is positively promoting the introduction of state-of-the-art inspection technologies and the development of original new technologies.

JFE Steel developed a new inspection technology utilizing matrix phased array UT which enables highly sensitive inspection of the center-of-thickness region of welds of LSAW (longitudinal submerged arc welding) pipes, and at the same time, also carried out a complete renewal of the automatic ultrasonic tester of the weld at its West Japan Works (Fukuyama District) pipe mill as a full phased array inspection system. The company also developed a new image detection technique called the "twin-illumination and subtraction technique" which enables clear detection of convex flaws on the surface of plate products, which had been subject to visual inspection, and installed an automatic detector using this technology in its East Japan Works (Keihin District) plate mill. This paper presents overviews of these new technologies.

2. Inspection Technology for LSAW Pipe Welds Using Phased Array UT

2.1 Background of Development

The welded pipe mill at West Japan Works (Fukuyama District) produces UOE steel pipes and bending steel pipes using steel plates as the base plates for pipe-making. Pipes are produced by press-forming or bending-forming the base plate into a round shape and then welding the abutting edges. Because cracks and incomplete penetration defects may occur during welding, ultrasonic inspections are carried out for assurance that the weld is a defect-free bond.

The technologies generally applied to ultrasonic inspection of the welded part are angle beam ultrasonic inspection for the inside and outside surfaces of the welded part, and the tandem method (in which the transmission part and receiving part are separated by

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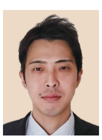
[*1] Senior Researcher Manager,
Cyber-Physical System Research & Development Dept.,
Steel Res. Lab.,
JFE Steel


[*2] General Manager,
Welded Pipe Dept.,
West Japan Works (Fukuyama),
JFE Steel


[*3] Assistant Manager,
Plate Rolling Plant,
Plate Rolling Dept.,
East Japan Works (Keihin),
JFE Steel

using two probes) for incomplete penetration that occurs in the center-of-thickness region of the weld. However, various issues arise in the tandem method for inspection of the center-of-thickness region of the weld, including deflection of the ultrasonic propagation path, which is easily affected by the shape of the weld, the inability to transmit the ultrasonic wave to target positions, the narrow detectability range in the circumferential direction, and the difficulty of adjusting the angles and locations of the two probes used in the tandem method[1]. Therefore, as an alternative to the tandem method, JFE Steel developed the ultrasonic direct incidence method, in which the ultrasonic beam is irradiated almost vertically on defects in the weld center by using a high refraction angle, and inspects welds by using an automatic ultrasonic tester based on this method[2]. At the time of its introduction, this automatic ultrasonic tester was a state-of-the-art device representing the culmination of nondestructive inspection technologies, and made an important contribution to supplying products with a high quality level. However, this device was renewed as a new automatic ultrasonic tester by applying phased array UT technology with the aim of realizing higher reliability and detectability.

2.2 Introduction of Phased Array UT Inspection Technology

Phased array UT inspection technology uses an ultrasonic probe in which multiple small ultrasonic transducers are arranged in a line or matrix. Control of the transmission/reception angle and focus position of the ultrasonic beam is possible by controlling the timing of transmission/reception by these small UT transducers[3].

In conventional UT inspections, signal variations occur due to the differences in the velocity of ultrasonic wave depending on the type of steel and changes in the incidence angle caused by backlash of the probe holding mechanism. If phased array UT technology is applied, differences in the velocity of ultrasonic wave depending on the type of steel and the effect of changes in the incidence angle due to backlash of the probe holding mechanism can be reduced by performing flaw detection (sectorial scan) while electronically swinging the angles of transmission and reception. Moreover, adjustment work can be simplified because the angle can also be swung widely during angle adjustment.

Photo 1 shows the appearance of the renewed automatic ultrasonic tester, and **Fig. 1** and **Table 1** show the system configuration and main specifications, respectively. Because the automatic ultrasonic tester comprises two manipulators, it can respond to diverse customer inspection specifications. In inspections using only one manipulator, it is possible to move smoothly to the next inspection, without lost time for device exchange or adjustment, by setting and calibrating the standby manipulator for use with the next lot. In addi-

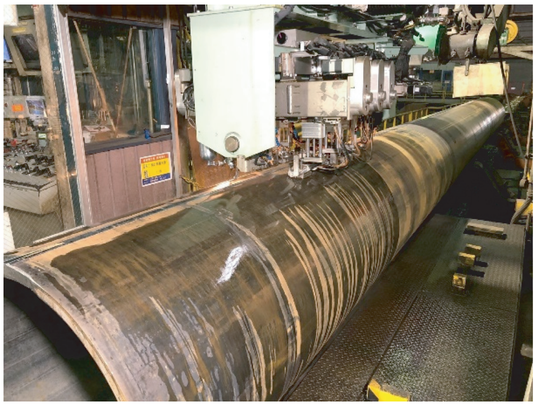


Photo 1 Renewed automatic ultrasonic tester

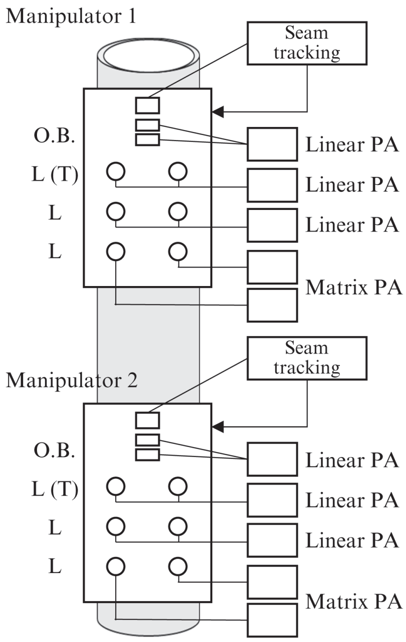


Fig. 1 System configuration of automatic ultrasonic tester

Table 1 Specification of automatic ultrasonic tester

Item	Specification
Size of pipe	Diameter 400-1 422 mm Thickness 6.5 mm-50.8 mm Length 5.5 m-19 m
Conveying speed	1 mpm-30 mpm
Inspection method	Inner zone, Outer zone: Angle method Middle zone: Direct incident method
Ultrasonic frequency	5 MHz
Coupling method	Water gap 0.5 mm-1.0 mm
Seam tracking	±2 mm

tion, a weld seam tracking system enables tracking control of the weld seam with accuracy within ±2 mm in the circumferential direction with the manipulators.

Each manipulator has one set of array probes for on-bead flaw detection and 3 sets of probes for L flaw detection. Among the array probes for L flaw detection, one set can also be used for both L and T flaw detection. Linear array probes are arranged for on-bead flaw detection and L flaw detection and T flaw detection of the inside and outside surfaces of the welded, and the newly-developed matrix array probe is arranged for flaw detection of the center-of-thickness region of the weld. The inspection method using the newly-developed matrix array probe is explained in the following section.

2.3 Direct Incidence Method Using Matrix Array UT

As mentioned previously, the ultrasonic direct incidence method is a method in which the ultrasonic beam is irradiated vertically with respect to incomplete penetration defects in the center-of-thickness of the weld. **Figure 2** shows the relationship between the ultrasonic refraction angle and echo transmittance. In the conventional angle beam ultrasonic inspection method, inspections are performed using a refraction angle of up to about 70°, but in contrast, an angle of 65°to 83° is used in the direct incidence method. Echo transmittance is decreased when the refraction angle is increased, as shown in Fig. 2. As a longstanding problem of the direct incidence method, inspections with an adequate S/N ratio were not possible due to this decrease in echo transmittance. JFE Steel applied digital signal processing (chirp pulse compression processing, synchronous addition processing) to this problem [2), and realized practical application of this inspection method by increasing the S/N ratio [4). However, application of the digital signal processing technologies available until now had led to large cost increases. Therefore, when applying the phased array UT technology, JFE Steel developed an ultrasonic inspection method which combines the matrix array probe and the direct incidence method, as shown schematically in **Fig. 3**, with the aim of securing a high S/N ratio by a new technique [5). As a result, JFE Steel realized a technology that compensates for the decrease in sensitivity when using a high refraction angle by absorbing the effects of angle changes due to variations in incident angle by scanning in the plate thickness direction, and making it possible to focus the beam in the longitudinal direction by using the matrix array probe. Moreover, the matrix array probe was designed to support inspections of a wide range of pipe-making sizes with one type of array probe, while also obtaining a sufficient ultrasonic beam focusing effect.

Figure 4 is an example of a signal chart in an inspection of a flat bottom hole with a diameter of φ3 mm machined in the center-of-thickness of a steel pipe with a wall thickness of 12.7 mm and outer diameter of 56 inches. When inspecting this pipe size, the refraction angle necessary for vertical irradiation of the ultrasonic beam on the flaw is 82°. The developed technology made it possible to detect the flaw with a high S/N ratio of 26 dB in spite of the greatly reduced echo transmittance due to this high refraction angle.

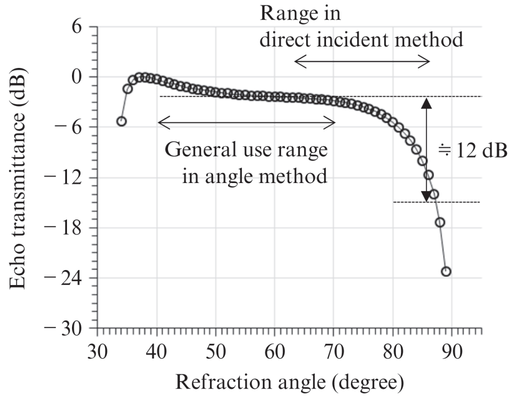


Fig. 2 Relation between refraction angle and echo transmittance

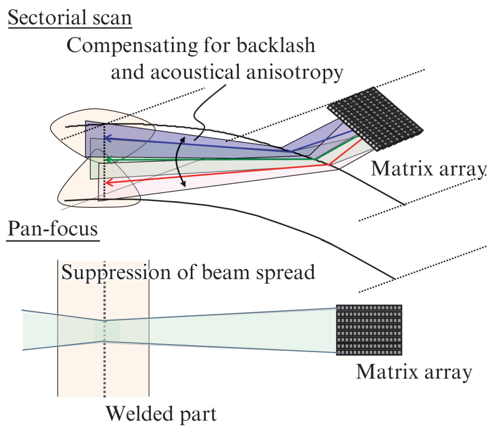


Fig. 3 Direct incident method at the center of wall thickness of welded part using matrix array probe

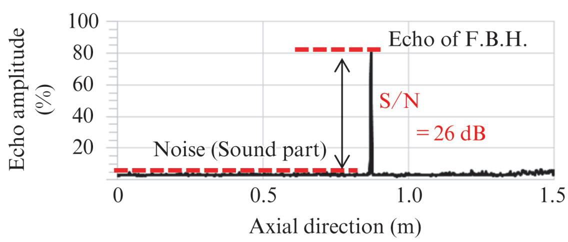


Fig. 4 Example of inspection chart

2.4 Examples of Inspection of Actual Pipes by Renewed Ultrasonic Tester

Table 2 shows the detectability and repeatability of detection of artificial flaws machined in actual pipes. The sizes of the pipe used in this detection experiment were outer diameter (O.D.) 18 inches × thickness (t) 12 mm, and O.D. 36 inches × t 38 mm. The detected flaws were a through-hole with a diameter of φ1.6 mm in the pipe weld and a flat bottom hole with a diameter of φ3.0 mm machined in the weld center-of-thickness ("middle" in the table). It should be noted that the flat bottom holes in the O.D. 36" pipes were machined at the 42 % thickness position and the 58 % thickness position.

The φ1.6 mm through-hole was detected by the angle beam method targeting the inside surface and outside surface using the linear phased array probe for L flaw detection, and the φ3.0 mm flat bottom holes were detected by the direct incident method using matrix array UT. Detection of each flaw was repeated 8 times. The average value and repeatability (variation) of the S/N ratios for the artificial flaws in this experiment were arranged as shown in Table 2. Although the inspection standard for pipe welds requires an S/N ratio of 10 to 12 dB or higher, detectability which ample satisfies these values was obtained. Furthermore, satisfactory results were also obtained for repeatability.

The newly renewed automatic ultrasonic tester suppresses the influence of differences in the velocity of ultrasonic wave depending on the steel type, backlash of the probe holding mechanism, etc., and contributes to quality assurance of welded pipe products by providing a high S/N ratio and good repeatability.

Table 2 Example of detectability

Pipe size	Defect type	S/N ratio Average (8 times)	Repeatability 3σ (8 times)
O.D. 18" t12 mm	T.D.H. 1.6 mm Inner	20.3 dB	1.4 dB
	T.D.H. 1.6 mm Outer	18.2 dB	0.7 dB
	F.B.H 3.0 mm Middle	27.2 dB	0.6 dB
O.D. 36" t38 mm	T.D.H. 1.6 mm Inner	21.8 dB	2.2 dB
	T.D.H. 1.6 mm Outer	22.1 dB	1.4 dB
	F.B.H 3.0 mm 42% middle	25.8 dB	1.2 dB
	F.B.H 3.0 mm 58% middle	28.1 dB	0.5 dB

3. Quality Assurance of Surface of Plate Products by Applying Twin-Illumination and Subtraction Technique

3.1 Background of Development

Because flaws sometimes occur on the surface of plate products during rolling and conveying, surface inspections are performed to ensure that products with this type of flaw are not released to customers.

In the field of steel sheets such as automotive steel sheets, introduction of surface inspection devices utilizing high speed camera technology has progressed, and inspections have been automated [6]. However, little progress has been made in automating surface inspections of plate products and other steel products which are covered with scale (iron oxide film), and the main practice is still visual inspection by an inspector. As one reason for this, when plate products are inspected, it is difficult to distinguish actual flaws from the surface pattern of flaw-free parts because plates have a rougher surface quality than steel sheets.

JFE Steel developed a new inspection technology called the "twin-illumination and subtraction technique [7]" which enables automatic inspection of the surface of plate products, and introduced this technology at its East Japan Works (Keihin District) plate mill.

3.2 Principle of Inspection Technology

The object of the developed inspection technology is flaws that are both open and concave. Concretely, this means flaws that occur as a result of foreign matter rolled into the plate by the rolls, open scabs and similar flaws. **Figure 5** shows the principle of the developed technology. Light is irradiated on the surface of the inspection target from two directions at different timings, and the respective images are capture by a camera (2-dimensional area sensor). Because the normal pat-

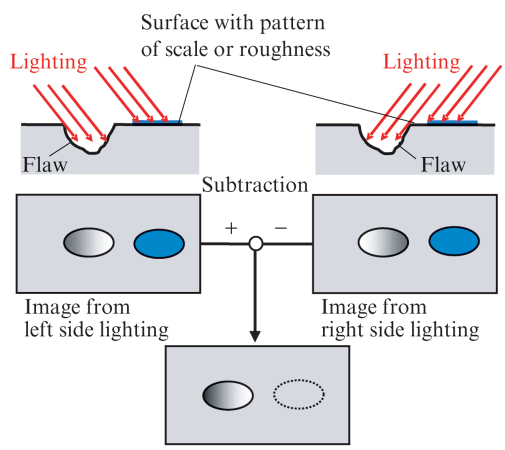


Fig. 5 Principle of twin-illumination and subtraction technique

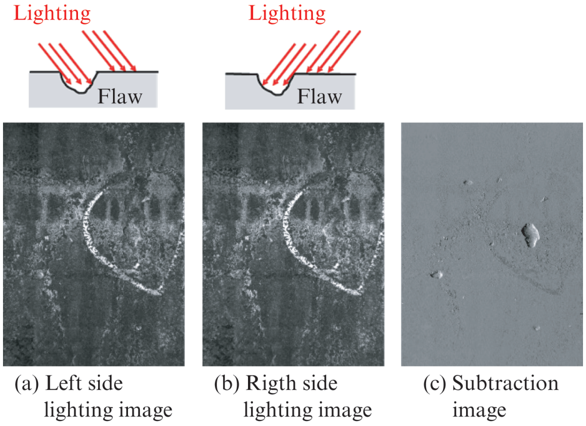


Fig. 6 Effect of developed technique

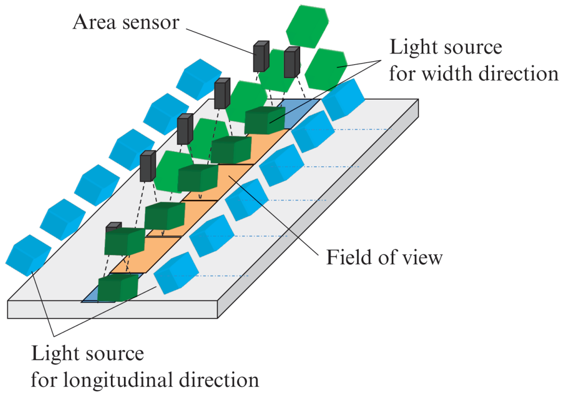


Fig. 7 Overview of automatic surface inspection system for steel plate

tern of the plate surface is flat, there is no difference in the shadows due to the direction of the light source in the two captured images. On the other hand, in parts with concave flaws, the shadows are different depending on the difference in the direction of the light source. Therefore, if the difference between the two images is calculated, the surface pattern part is cancelled out, and only the concave flaw is emphasized. **Figure 6** shows the result of a verification of the effect of the developed technology by a laboratory experiment. The experiment was conducted using a test piece with a natural flaw. The test piece is covered with adhering scale, and a white marking has been made around the natural flaw. Although it is difficult to recognize the flaw from only the images captured with lighting from either the left side or the right side, as shown in Fig. 6(a) and (b), the pattern in the flat part of the surface is cancelled in the subtraction image in Fig. 6(c), and the flaw is clearly visible.

In applying the developed technology to inspection targets during conveying, it is important to ensure that there is no deviation in the positions of the images captured with lighting from the two sides. This problem was solved by using strobe lights for lighting from the two sides and photographing at a speed of 10 microsecond [7].

3.3 Overview of Automatic Surface Inspection System

Figure 7 shows an overview of the automatic surface inspection system introduced at the plate mill. The automatic surface inspection system was installed upstream side of the in-line visual inspection station, where visual inspections of the top and bottom sides of plates are conducted. In order to inspect the entire top and bottom surfaces of plate products, multiple cameras were installed so as to cover the full width direction [8].

In the case of narrow elongated flaws, if light is irradiated from the direction parallel to the longitudinal direction of the flaw, an adequate subtraction effect will not be obtained because the slope of the flaw is gentle in comparison with the part without a flaw, and as a result, the signal will be weak. Since narrow elongated flaws also occur on plate products, a configuration of 2 light sources for lighting in the longitudinal direction and 2 light sources for lighting in the width direction for each camera was adopted.

In the twin-illumination and subtraction technique, subtraction processing is performed after applying various types of image processing such as shading correction, etc. to the acquired images. Flaw candidates are then extracted, and feature values such as the brightness pattern, etc. are calculated for each flaw candidate. Whether a candidate is a flaw or not is judged based on the feature values. If the candidate judged to be a flaw, the type of flaw, i.e., scab or roll flaw, is also judged. These flaw judgments are made by a decision tree model constructed by machine learning. The positions of indications that are judged to be flaws are displayed as guidance to the operator of the in-line inspection station, and the operator double-checks the flaws for which guidance is received and prevents the release of products with flaws. The guidance which the system provides to the operator includes a display of the location of the flaw on the full surface of the plate and an image of the actual flaw.

Figure 8 shows an example of a guidance screen when the automatic surface inspection system detects a periodic roll flaw. When a flaw is detected, the inspection result screen shown in Fig. 8 is displayed to the operator immediately before the detected product reaches the in-line inspection station. The image of the detected flaw is also displayed at this time. Because products pass under the in-line inspection station, the system also displays the position of the product relative to the in-line inspection station at the time of display, and gives an alarm by sound when the detected flaw is

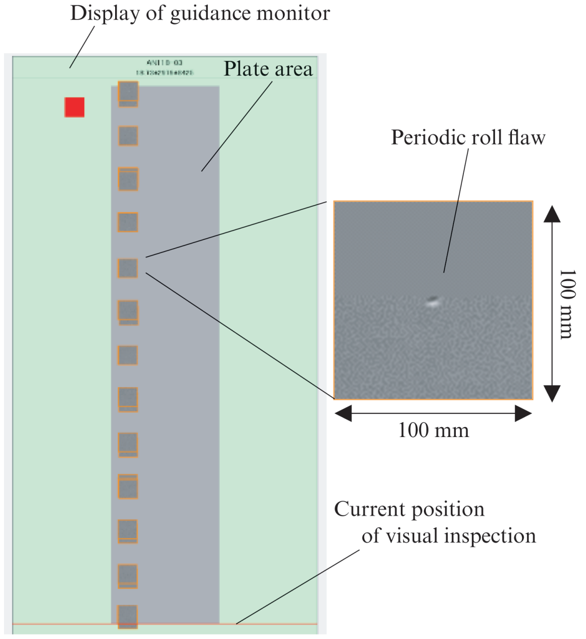


Fig. 8 Guidance monitor of automatic surface inspection system

near in order to enable easy checking of detected flaws.

Realizing this system has made it possible to detect surface flaws with high reliability, and is contributing to quality assurance of plates by preventing the release of products with flaws.

3.4 Construction of Flaw Judgment Algorithm

As mentioned above, flaws are judged by a decision tree model constructed by machine learning. In the construction of the decision tree model, machine learning must be performed by comparing the feature values of flaw candidates measured by the automatic surface inspection system and teaching data in which those values were correctly judged as flaws or not flaws. In conventional visual inspections, the flaw judgments are not quantitative, and judgments can be affected by differences among individual operators.

Therefore, in order to eliminate the influence of variations in judgments depending on the operator, information on the width, length, depth and area of parts that were considered to be surface defect candidates in visual inspections was collected by using laser profile measurement equipment, the definitions of flaws were expressed in quantitative terms, and these were used as data for supervised learning. Since it is also necessary to construct a flaw judgment model that enables detection without overlooking flaws, a new machine learning method using a judgment algorithm was developed[9]. Normally, attempting to increase the flaw detection rate will result in an increase in over detection (i.e., judgment that normal positions are flaws), and conversely, attempting to reduce over detection will result in flaws being missed more easily. Conventionally, the user could not adjust the levels of the detection rate and the over detection rate. However, changing the difference in the ease of mistaken judgment of flaw and non-flaw data has made it possible to adjust the intended detection rate automatically in the developed system. In this judgment model, the allowable over detection rate was set in advance, and machine learning was carried out after adjustment to a detection rate of 100 %.

It is also possible that new flaws and surface changes may occur due to changes in the manufacturing method or equipment. Because newly-occurring flaws and surface changes are not included in the existing flaw judgment model, the risk of over detection or failure to detect flaws is conceivable. Therefore, a function which makes it possible to reconstruct new flaw judgment models based on newly added flaw definitions was devised. In this function, 3D measurements of the shapes of flaws are carried out periodically, and whether the flaws are actually flaws or not is determined in advance and added to the flaw definition database. This system can be operated easily, even without specialized knowledge. The introduction of this system makes it possible to maintain the detectability of the judgment model permanently.

4. Conclusion

Among the inspection technologies which support the quality of steel products produced by JFE Steel, this paper has introduced an automatic ultrasonic tester which enables inspection of welds of steel pipes with high sensitivity and high repeatability, and an automatic surface inspection system which makes it possible to cancel disturbances due to the normal surface quality of plate products and detect harmful concave flaws.

In the future, JFE Steel will continue to make every effort to develop and introduce advanced high-reliability inspection technologies, and will work to improve the quality of steel products.

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