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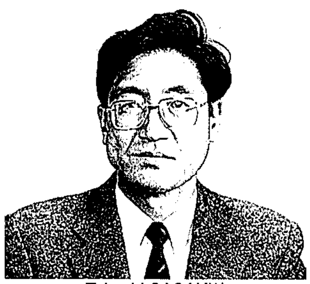
Development of Non-Destructive Inspection Technology of Titanium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Abstract

This paper describes the recent technological advances on the nondestructive testing (NDT) of titanium products, which was surveyed through the activities of the Japan Titanium Society. Titanium tubes are tested by ultrasonic testing (UT), eddy current testing (ET) or leakage testing (LT) based on JIS or ASTM standards, whereas titanium sheets, rods or wires are tested according to the requirements of customers or the specifications of manufacturers themselves, because no standards are available. Titanium sheets are tested by UT or liquid penetrant testing (PT). Titanium rods and wires are tested by UT, PT or ET.

1. Introduction

Thanks to high specific strength, corrosion resistance, durability and light weight, titanium products (including titanium alloy products) are used in severe conditions such as heat exchangers for chemical and seawater desalination plants, condensers for thermal and nuclear power plants and engines for aircraft and automobiles. For this reason, highly stringent quality requirements are imposed on such titanium products and for quality assurance purposes, they are shipped after undergoing strict testing and inspections during their manufacturing processes, as well as at the final product stage. Non-destructive inspections constitute significant means of these tests and inspections.

This paper describes the non-destructive inspection methods practiced in Nippon Steel for quality control and quality assurance of its main titanium products, namely, sheets and plates, tubes, bars and wires. Advancements of non-destructive inspection technologies of titanium products are also described herein based on a report[1)] of the Non-destructive Inspection Subcommittee of the Japan Titanium Society.

2. Present State of Non-Destructive Inspection Technologies

2.1 Objects and Variety of Non-Destructive Inspection

Non-destructive inspection is characterized by its ability, as the name implies, to inspect the soundness of objects to be tested without destroying them. Therefore, by suitably selecting and combining various non-destructive inspection methods, the objects can be inspected in all the surfaces and in the entire length of all the pieces. Non-destructive inspection is employed for the purpose of detecting surface defects (scab, crack, dent, etc.) and internal flaws (inclusion, internal crack, etc.) and evaluating against standards set forth from the viewpoints of harm of each flaw, industrial applicability of the product, etc. whether the objects are acceptable or rejected.

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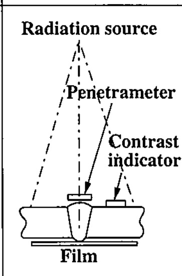
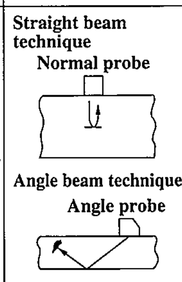
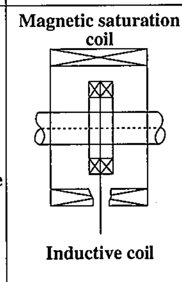
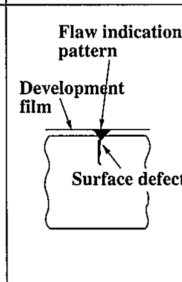
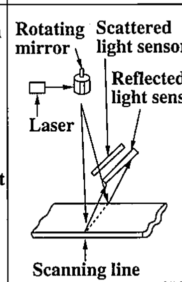
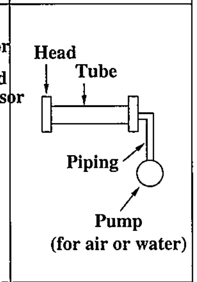
	Radiographic testing	Ultrasonic testing	Eddy current testing	Penetrant testing	Optical testing	Leakage testing
Schematic illustration of test method						
Applied physical phenomenon	Electromagnetic wave	Ultrasonic wave (elastic wave)	Electromagnetic induction	Penetration (capillarity)	Light	Water or air leakage
Applicable material	Metal and nonmetal materials	Metal and nonmetal materials	Conductive material	Metal and nonmetal materials	Metal and nonmetal materials	Metal and nonmetal materials
Detectable flaw	Surface, internal material	Surface, internal material	Surface (to some depth)	Surface	Surface	Through hole

Fig. 1 Comparison of NDI methods

Some people call non-destructive inspection (NDI) also the non-destructive test (NDT) or the non-destructive examination (NDE), depending upon the case. In this paper, the letters NDI as a common terminology and the letters NDT as a terminology to indicate evaluation tests are used according to the case.

The varieties of NDT applied to titanium products are as follows:

- Radiographic test (RT)
- Ultrasonic test (UT)
- Eddy current test (ET)
- Penetrant test (PT)
- Optical test (OT)
- Leakage test (LT)

These non-destructive test methods are compared in **Fig. 1** and their flaw detecting capabilities are qualitatively evaluated in **Table 1**. Since the flaw detection capability is different method by method, these methods are applied, individually or in combination, in consideration of the test objects and the flaws to detect.

Table 1 Flaw detection abilities of NDI methods

	Inspection method						
	Automatic scanning				Manual scanning		
Kind of flaw	UT	ET	OT	LT	RT	UT	PT
Surface defects (scab, crack, dent, etc.)	○	○	○	×	△	○	○
Internal flaws (inclusion, internal crack, blow hole)	○	△	×	×	○	○	×
Through defects (hole, crack)	○	○	○	○	○	○	○

Legend ○: detectable, △: difficult, ×: not detectable

2.2 Standards of NDI

Table 2 shows examples of Japanese and foreign standards applied to titanium products. As seen in the table, the Japanese Industrial Standard (JIS) sets forth six standards of NDI applicable to the titanium products, and ASTM sets forth one. JIS stipulates RT for welded joints, UT, ET and LT for tubes and PT for all initial materials and products. ASTM stipulates UT, ET and LT for titanium tubes for heat exchangers but, judging from the table, no NDI standards are set forth for flat products, bars and wires.

2.3 NDI Applied to Titanium Products

Table 3 shows NDI methods applied to titanium products during manufacturing processes and at the final product stage.

2.3.1 Flat products

Flat products of titanium are divided into heavy gauge plates and light gauge sheets. There is no standard requiring application of NDI

Table 2 Standards of titanium products applying NDT

Test	Standard		Object product
Radiographic test	JIS Z 3107-1993	Methods of radiographic examination for titanium welds by X-ray	Flat products and welded joints of tubular products (penetration thickness: 25 mm or less)
Ultrasonic test	JIS H 0516-1992	Ultrasonic inspection of titanium pipes and tubes	Seamless and welded tubes
	ASTM B 338-1995	Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers	Seamless and welded tubes
Eddy current test	JIS H 0515-1992	Eddy current inspection of titanium pipes and tubes	Seamless and welded tubes
	ASTM B 338-1995	Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers	Seamless and welded tubes
Penetrant test	JIS Z 2343-1998	Method for liquid penetrant testing and classification of the indication	Initial materials and final products
Leakage test	JIS H 4630-1994	Titanium pipes for ordinary piping	Seamless and welded tubes
	JIS H 4631-1994	Titanium tubes for heat exchangers	Seamless and welded tubes
	ASTM B 338-1995	Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers	Seamless and welded tubes

Table 3 Application of NDT in manufacturing processes

Product		Process stage (NDT applied as required)		
		Initial material	Rolling (quality control)	Final products (quality assurance)
Flat	Heavy plate	PT of slabs	-	UT, PT
	Thin sheet (including coil)		-	PT
Tube	Seamless tube	UT, PT of billets	-	UT, ET, LT
	Welded tube	ET of slit strips	-	RT, UT, ET, LT
Bar and wire	Bar	UT, PT of billets	-	UT, PT
	Wire		ET (hot)	ET

to the final flat products of titanium. Instead, PT is applied to slabs and the slabs are sent to rolling processes after removing detected flaws for preventing them from recurring at subsequent processes. In the case of heavy plates, UT and/or PT is/are applied according to customer requests. PT is sometimes applied to light gauge sheet products cut to length. The optical flaw test recently used for steel sheet products is not included in the standards for titanium sheets, owing to the facts that its inspection speed is low and that inspection criteria for different product applications are complicated, and only visual inspection is commonly used.

2.3.2 Tubular products

Tubular titanium products are divided in terms of manufacturing process into welded tubes and seamless tubes. ET is sometimes applied to slit strips of cold rolled coils used as the material of welded tubes, but this is not a common practice. The final tube products after forming, welding and cutting to length are inspected by a combination of ET and UT. Sometimes RT is applied to randomly selected samples as required. LT (pneumatic pressure test, in this case) is additionally conducted to detect through holes.

In the case of seamless tubes, material billets are sometimes tested by UT and/or PT, and the billets are sent to the subsequent hot extrusion process after removing the flaws, if any. Final seamless tube products obtained through extrusion or a sequence of extrusion, cold rolling and drawing are inspected by UT and ET used in combination, and then LT (hydraulic pressure test, in this case) is conducted, as required. Some customers request ET by the inner coil method before final shipment.

2.3.3 Bars and wires

UT or PT may be applied to billets before rolling into bars or wires. UT and/or ET is/are applied to final bar products, hot ET is applied to wires during rolling for quality control purposes and, further, ET is applied to cold drawn wires. Again, there is no standard requiring application of NDI to the final products of bars or wires, and NDI is conducted on the final bar and wire products on customer requests.

2.4 Present Practice of NDI

2.4.1 NDI of titanium flat products

(1) Ultrasonic test

UT is carried out off line and manually on plates 10 mm or so in thickness using a portable ultrasonic tester by straight beam technique. In the case of light gauge sheets 0.2 to 2 mm in thickness for heat exchanger use, some attempts of lamb wave ultrasonic test have been made using a wheel search unit.

(2) Penetrant test

Defect detection of an entire surface has been put into practice applying the solvent-removable visible dye penetrant/non-aqueous development method. For improving workability, the water-washable visible dye penetrant/non-aqueous development method is sometimes practiced recently, but the method requires a waste water treatment facility.

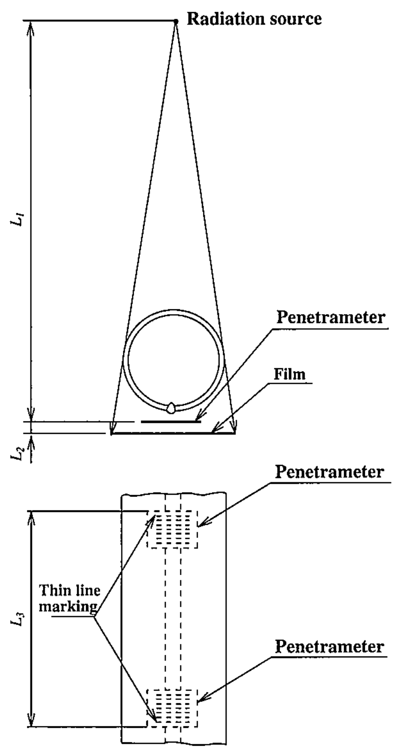
2.4.2 NDI of titanium tubular products

(1) Radiographic test

X-ray tests are carried out to confirm soundness of welded joints. **Fig. 2** shows the method of the X-ray photometry according to JIS Z 3107. An aluminum penetrameter and an X-ray quality indicator used to be used under JIS Z 3107, but the standard was revised substituting the aluminum penetrameter with a titanium penetrameter to make the test easier. **Photo 1** shows an example of X-ray film of a welded titanium tube.

(2) Ultrasonic test

The same flaw detection method shown in **Fig. 3** is applied to both welded and seamless tubes, wherein a tube is transferred in the axial direction and a probe emits and receives an ultrasonic wave, while rotating around the tube for scanning in the circumferential and axial directions by the angle beam technique. The angle of incidence of the ultrasonic wave is important for effective detection of flaws in the outer and inner surfaces of the tubes. **Fig. 4** shows test results of thin wall thickness welded tubes. As seen



L_1: distance from radiation source to penetrameter
L_2: distance from penetrameter to film
L_3: effective length of area to inspect

Fig. 2 Arrangement for X-ray radiography of longitudinal welded seam of tube

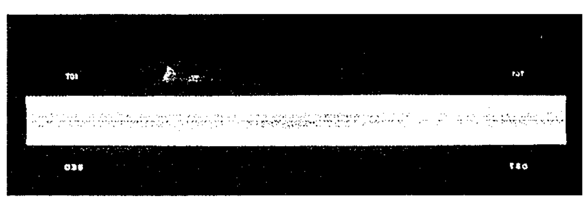


Photo 1 Example of X-ray radiograph of welded titanium tube (diameter 24.5 mm, wall thickness 0.5 mm)

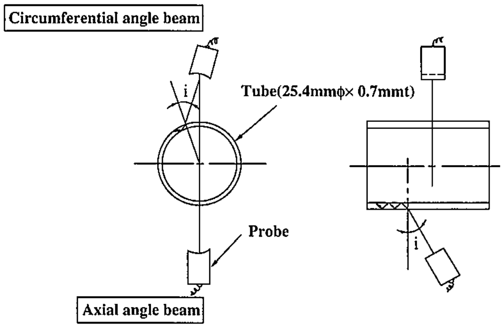


Fig. 3 Ultrasonic test method

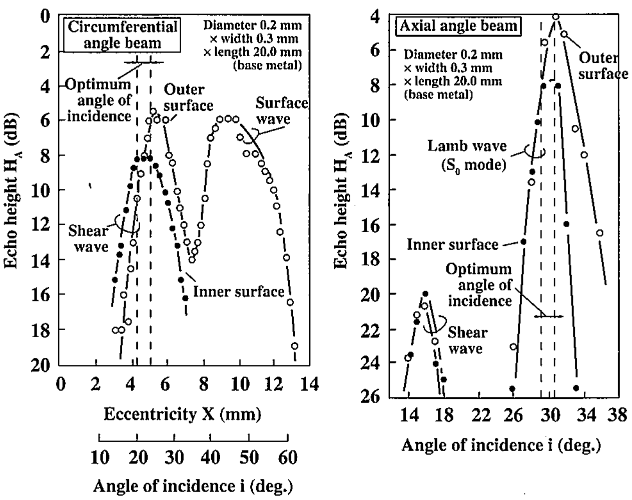


Fig. 4 Relation between angle of incidence and echo height

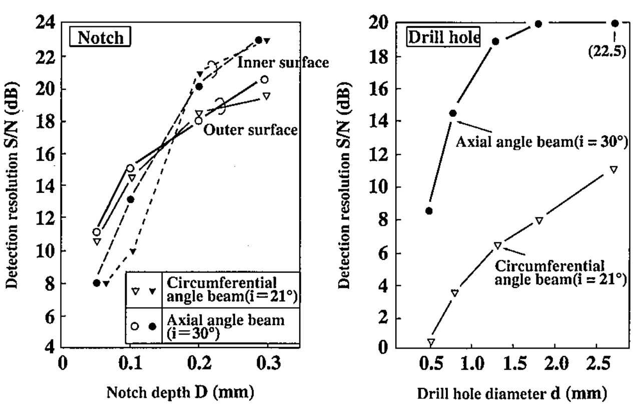


Fig. 5 Detection characteristics of ultrasonic test

in the figure, shear wave (angle of incidence i: 20 to 24°) is most suitable for the circumferential angle beam scanning, and lamb wave (i: 29 to 31°) for the axial angle beam scanning. Detection characteristics of an artificial flaw under the above conditions are shown in **Fig. 5**. An artificial reference notch 0.1 mm in depth is detected at S/N ≧ 10 dB, which satisfies what is required in ASTM B 338. Although it is difficult to detect a through drill hole 0.79 mm in diameter by this method, drill holes are not specified in any of the standards.

(3) Eddy current test

ET is applied to both welded and seamless tubes and the flaw detection method is the same for the two. The encircling coil methods shown in **Fig. 6** are employed for ET for tubes, wherein

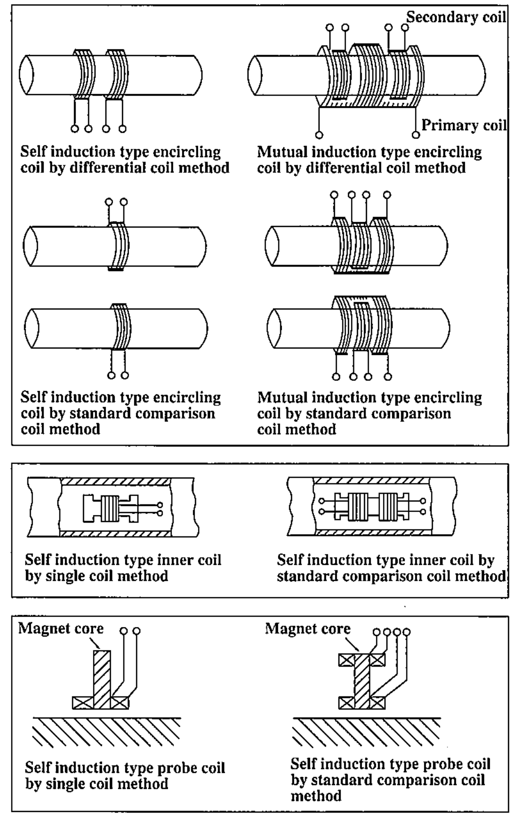


Fig. 6 Classification of eddy current test methods

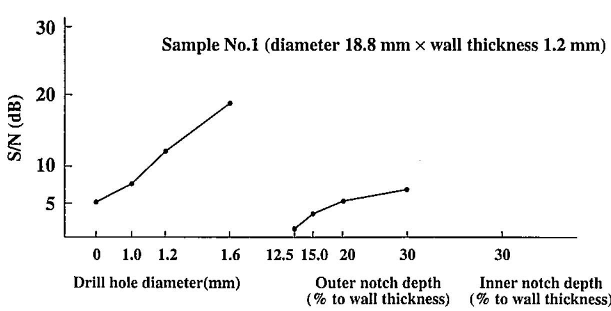


Fig. 7 Detection characteristics of eddy current test (joint test)

the differential coil method using the self induction type or mutual induction type coil arrangement is used for scanning. In **Fig. 7** showing examples of flaw detection ability, it is understood that a reference hole 0.79 mm in diameter and a reference notch having a depth of 20% of the wall thickness are detected at S/N ≧ 3 dB, satisfying ASTM B 338. By the inner coil method, test objects are scanned using a self-induction type differential coil and multiple frequencies, and flaws are detected through phase analysis after signal processing.

(4) Leakage test

Hydraulic or pneumatic LT is selected depending on the test object. The immersion pneumatic test is applied in Japan to welded tubes. The differential pressure test, in which the pressure difference between two tubes tested in parallel is measured for detecting leakage, is accepted in ASTM B 338, though not in JIS.

2.4.3 NDI of titanium bars and wires

(1) Ultrasonic test

The straight beam and angle beam techniques are combined for

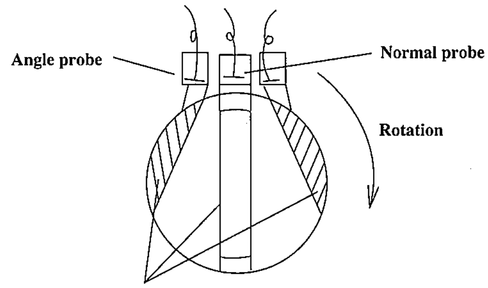


Fig. 8 Principle of ultrasonic test of round bars

UT of round bars in order to cover the whole sectional area. **Fig. 8** shows the principles of the flaw detection. All the inner and surface portions are scanned while the bar is rotated and transferred longitudinally.

(2) Penetrant test

PT is carried out as the final inspection before shipment covering the whole sectional area by the solvent-removable visible dye penetrant/non-aqueous development method.

(3) Eddy current test

ET is carried out in hot using the encircling coil method for quality control purposes during rolling of wires. For products after cold working, the encircling coil methods shown in Fig. 6 and the rotating probe coil methods are used, individually or in combination. The encircling coil methods are used for detecting circumferential defects such as dents, and the rotating probe coil methods for longitudinal defects such as cracks.

2.5 Standardization of NDI of Titanium Products

Standardization of NDI of titanium products under JIS has been promoted mainly by the Japan Titanium Society organizing its member companies, and the three standards of RT, UT and ET shown in Table 2 were established and revised in 1992 and 1993. The Society manufactures and markets the titanium penetrameter for RT included in JIS at the revision mentioned in 2.4.2 (1).

3. Latest Trends of NDI

Creation type research and development for new international standards are a typical example of the latest trends in the industry. In view of the fact that the world is moving toward formation of a single global market, international standards of titanium materials and products have to be established under ISO or a similar framework. The above activity is promoted by Japanese titanium-related industries in close cooperation with the public sector. The Japan Titanium Society promoted standardization in the fields of analysis tests and NDI from 1998 to 2000 under the framework of "The Standardization of Test and Evaluation Methods of Pure Titanium" under a governmental subsidy. The subjects of the Society's development studies in the field of NDI were selected as follows, in line with the creation type research activities, aiming at creation of new standards of flaw detection methods not yet practiced in the Japanese titanium industry.

(1) Inspection method of surface defects of flat products laser scanning method, CCD camera method

(2) Inspection method of internal defects of flat products ultrasonic test method using lamb wave

(3) Inspection method of surface defects of bars rotating probe type eddy current test method

(4) Leakage test method of welded tubes differential pressure method

The outline of the latest activities related to the above subjects are as follows.

(1) Optical inspection method of surface defects of flat products

Five titanium producers tested the laser scanning method and the CCD camera method regarding their detection performance of non-artificial flaws of titanium flat products and their industrial applicability was confirmed.

(2) Ultrasonic test method of internal defects of flat products

In order to enhance sensitivity of the wheel search unit used for the ultrasonic test of thin sheet products 0.5 to 1.5 mm in thickness, improvement of the wheel was studied. An optimum frequency was defined from the viewpoints of flaw detection ability and attenuation.

(3) Rotating probe type eddy current test method of surface defects of bars

The mutual induction type differential coil was found to be suitable as the inspection coil for the rotating probe type eddy current test of surface defects of bars. The coil actually detected an artificial reference notch 0.05 mm in depth.

(4) Leakage test method of welded tubes differential pressure method

The relations of differential pressure to the sectional area of flaw, the amount of leakage, test pressure and inner volume of tested tubes were made clear by a differential pressure test using specimens having an artificial through hole. As a result, the method proved capable of detecting a through hole 0.03 mm in diameter.

The plan for the future is to prepare daft standards based on the above results to propose to ISO as new international standards together with the "Ultrasonic Test of Titanium Tubes" and the "Eddy Current Test of Titanium Tubes" already included in JIS. (For further details of the creation type research and development for new international standards, see the reference literature 2).

4. Ending Remarks

Demands for titanium products have expanded in the fields of industrial materials and consumer goods thanks to their excellent material properties, and the industry is expected to grow further. Expansion of international trade is indispensable for further growth of the demands for the titanium products and, for this end, in view of the fact that no standards related to titanium products are included in the ISO system, establishment of international standards of the products is awaited. Product standards have to include specifications of test and evaluation methods, in which NDI forms a significant part.

NDI constitutes an indispensable part of the manufacturing technology for the quality control and quality assurance of the titanium products and, in this regard, the most appropriate NDI technologies have to be established as standards for various kinds of titanium products. This is exactly the reason why the Japan Titanium Society is taking initiative in the establishment of new ISO standards based on the draft standards for the titanium flat products, bars and wires prepared through cooperation of its member companies together with the existing titanium-related JIS standards.

The understanding and cooperation of related people will be greatly appreciated.

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1) Sasaki, T. et al.: Non-Destructive Inspection of Titanium Products, Titanium Japan. 46 (2), 116 (1998)
2) Development of International Standards for Supporting New Industries, "Standardization of Test and Evaluation Methods of Pure Titanium," Report of Study Assigned by The General Development Organization for New Energy and Industrial Technologies for fiscal years 1998 and 1999