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Technical Offer

AIS2100

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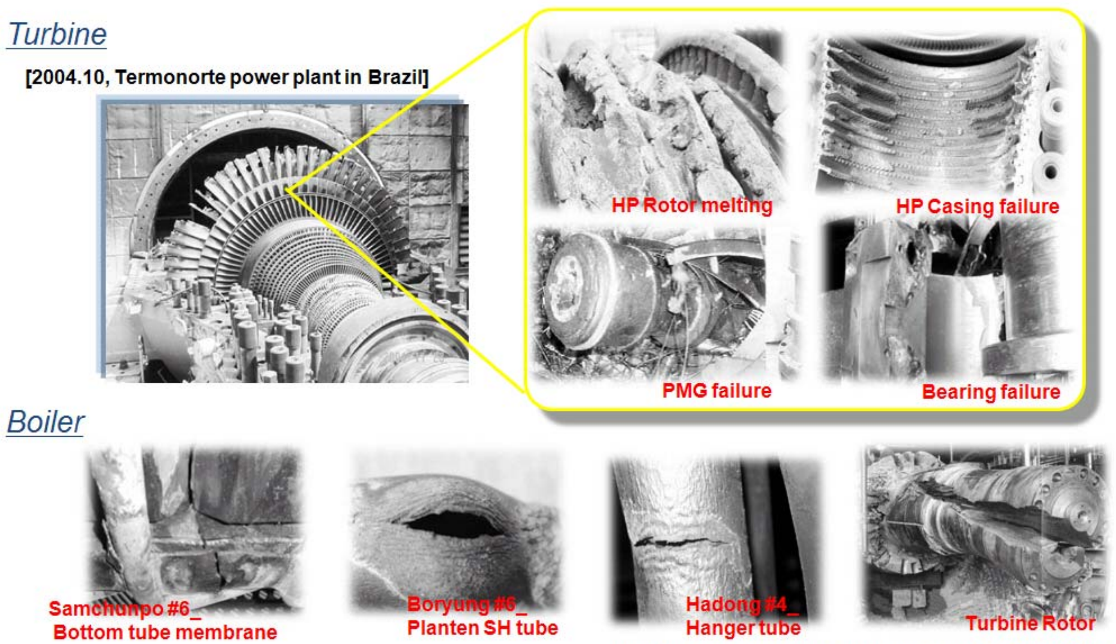
Introduction

1. Introduction

Carbon steel, alloy stainless steel, zirconium alloy, nickel alloy and etc, that are commonly used for the materials of power plant and oil refinery facilities, should maintain health of components and materials, and secure the high stability during life-time, since they face the unique environment of the facilities of high temperature and high pressure. From the initial stage of design, the materials of the equipment and facilities are selected and applied completing the standard and the regulatory requirement through the thorough function analysis and interpretation of safety based on characteristics test, material design code, safety standard, requirement of manufacture specification, operation experience of the equipment and so forth out of the property data of the materials. In other words, the strict management is required at operation as well as design and selection of materials for the design, manufacture, safe operation and control, and extension of life time of equipment, by which the fundamental causes of damage and own issues occurred at operation will be resolved.

Materials of equipment are occurred the aging problem that reduces gradually the quality of material as using time flows, due to mechanical, chemical and thermal effects, and breakdown or failure is caused by the operational trouble due to various damages of change of dimension, shape and internal structure. Especially change of mechanical property of the materials significantly degrades safety and health of the entire facility, and reduces the life span. In this connection, it is of essence to investigate the characteristics and behavior of structure materials in the operating environment of the equipment, and the accurate evaluation of material property change by time is important as well to acquire the soundness data of the materials. But it is almost impossible to collect specimens from the equipment in use, and it is considerably difficult to evaluate the material property by performing the conventional destructive test. Thus nondestructive evaluation technologies such as X-ray, ultrasonic method and so on are widely used, that utilize the feature detecting nondestructively the minute change of unique property of the material such as radiation, elastic, electromagnetic and thermal properties caused by the change of mechanical properties due to internal defects, machining, welding state, material composition and structure characteristics. However, these indirect methods to evaluate soundness have the limit to measure quantitatively mechanical properties. And it is required to establish the new method of nondestructive evaluation of property, since most of the materials have far different properties from the conventional single crystal materials, and as the existing standard nondestructive property evaluation methods cannot be applied to lots of cases under the application of new complex function and special environment.

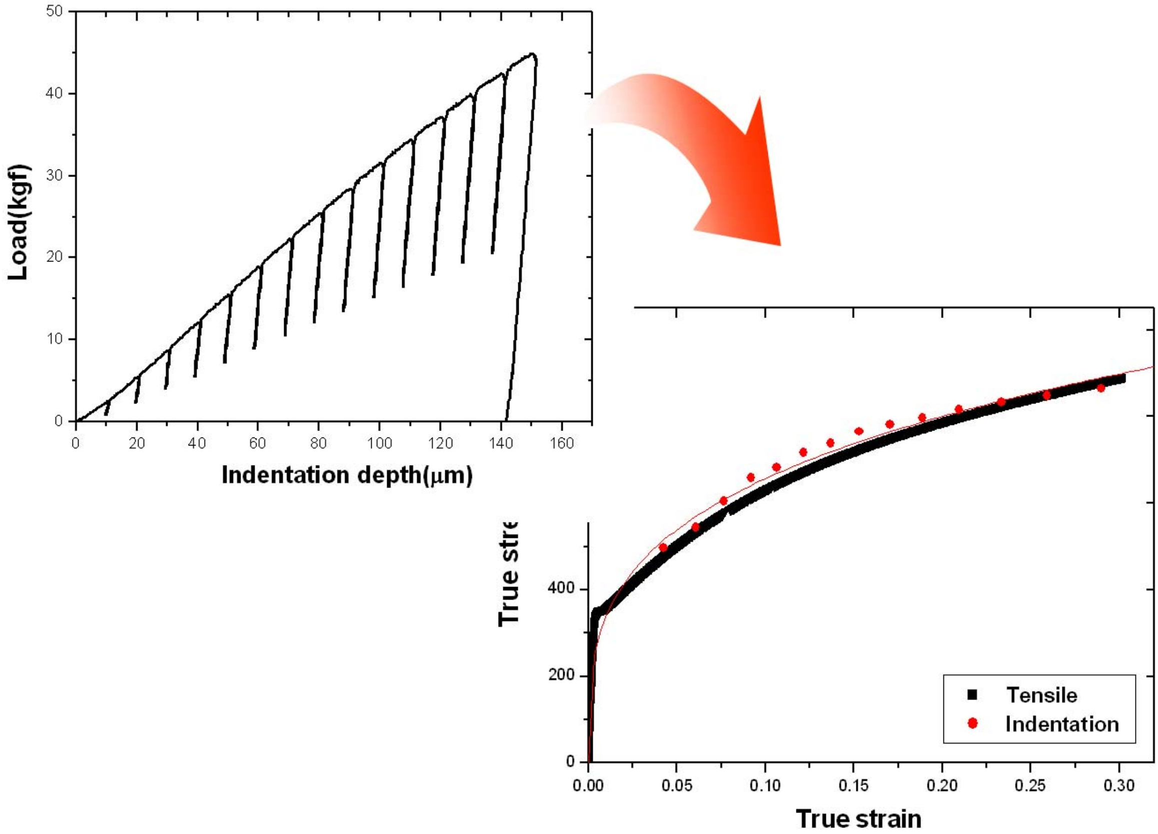
In addition to data of mechanical properties change, residual stress is the other important factor at investigating health and stability. Particularly residual stress distributed at weldment causes distortion of the structure shape, degrades fatigue-proof and toughness due to corrosion and plastic deformation by increasing the impact of chemically and mechanically environmental factors, and ultimately influences upon life span of the entire facility. It is fairly hard to measure accurately the condition of such residual stress, however, maintenance and repairs through the quantitative measurement are absolutely required, as it is the very important issue to ensure health of the actual nuclear power plant facility.



[Workshop on electronic tech., KECA, 2007]

2. Effect of Technology Introduction

In general, Instrumented indentation test is the technique measuring continuously the indentation depth according to the indentation load applied to materials to get indentation load displacement curve as the drawing, and evaluating the mechanical properties of target materials through the analysis of the curve. It is similar to the existing hardness test such as Vickers, Brinell and so forth, however, it does not measure directly the size of the indentation spot. And it has the advantage of acquiring various own properties of the material such as elastic module, tensile characteristics, fracture toughness and residual stress as well as existing hardness.



Besides, it is the nondestructive test method as well, since it can evaluate the change pattern as for the material that has the sectional property change such as weldment due to evaluating minute region less than hundreds of micrometers maximum., and leave only a very tiny spot on the material after test. It has the great advantage that it can be directly applicable to the structure under operation or installation where destructive test is not available due to the issue of collecting specimens for processing.

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AIS2100 (Advanced Indentation System 2100)

1. Introduction

Instrumented indentation tester is a measurement device that consists of the load sensor measuring applied load and the displacement sensor measuring indentation depth, and measures the final indentation load-displacement curve in real time by controlling the signal of the two sensors. Instrumented indentation tester is generally divided into nano, micro and macro indentation testers by load range. Nano/Micro indentation tester with the load range less than mN is mainly used for property evaluation of thin film, and most of the measured properties are nano hardness and elastic module. Manufacturers of nano indentation testing devices currently on the market are typically MTS (US), Hysitron (US) and Micro-Materials (UK). Macro instrumented indentation tester has the load range of kg unit, and is designed and fabricated with lightweight to carry easily as shown on the figure not only for the purpose of research but also of the industrial application. As for the measurable properties, evaluation of most of such mechanical characteristics as tensile properties, residual stress and fracture toughness is available in addition to hardness and elastic module.

2. AIS2100

AIS2100 which is the indentation type tensile property measuring equipment that measures tensile property by nondestructive method. It is designed to use both at laboratory and job site with smaller size than the conventional tensile testing equipment, and guarantees precision of measurement. Particularly it is the testing equipment that can effectively evaluate tensile properties which can not be tested by the conventional single axis tensile test, since it is difficult to make tensile specimens due to small size and complicated shape of the test subject or uneven distribution of tensile properties in the material. Furthermore, it can evaluate automatically in a few seconds, by the software of up-to-date indentation test technique, such final properties as yield strength, tensile strength, work-hardening exponent and elastic module through the analysis of indentation load-displacement curve immediately after the indentation test for 2 or 3 minutes, and the test result is provided to testers.

3. Merits of equipment

AIS2100 which is equipment of FRONTICS adopting instrumented indentation, by the development know-how for a decade or longer and introduction of the new technology, has various advantages for field application. It also has lots of advantages for convenience of users such as functional enhancement of internal sensor and data processing, optimized attachment for field application and device software as well. Besides, it carries out testing and analysis according to international standard ISO/TR29381 for reliability of the test result.

Merits of AIS2100

- Stable depth sensor
- High-performance system for data processing
- Self calibration tool
- Compact hardware configuration
- Optimized attachments
- Portable battery
- Wireless communication by Bluetooth module
- Portable grinder
- Powerful Software

Table.1 Comparison of major specification

Item	Other equipment	AIS2100
Depth sensor type	LVDT type	Linear scale type
Depth resolution	0.2 um	0.1 um
Data process	12 bit	16 bit
Load resolution	100 gf	7.6 gf
Data acquisition rate	10 points/sec	100 points/sec

(1) Stable depth sensors

AIS2100 adopted the sensor of linear scale type with higher resolution of optical means for evaluation of various properties. Depth sensor of AIS2100 is a non-contact optical encoder designed for position feedback solutions. It used a common reflective tape scanned by a readhead chosen from a range of options offering industry standard digital square wave or analogue sinusoidal output signal formats. It gives proven performance benefits together with high tolerance to scale contamination. It is an ideal feedback solution wherever precision controlled movement is required. The sensor enabled users to evaluate residual stress as well as tensile properties and fracture toughness owing to its twice higher resolution than the equipment of other companies. Furthermore, linear scale type sensor can be used for 5 years or longer without any deformation, and special calibration is not necessary for the sensor, while existing depth sensor has the disadvantage of performing calibration due to deformation of sensor when it is used for a long period.

Depth sensor head unique
: RENISHAW RGH24 – Digital and analogue readhead system

Document	tec04-02 readhead reliability.doc		Page 1 of 1
Issue	1	Date of issue 30 June 2000	Controlled distribution to EPD CD-ROM only

RENISHAW

ENCODER PRODUCTS DIVISION

Encoder system reliability

This document gives information on readhead reliability and MTBF calculation.

$$\text{MTBF} \quad (M) = \frac{pt}{n}$$

where

where	p	installed population of readheads
	t	average length of service
	n	total relevant failures

From our records (yearly production figures and failure data), readhead MTBF in continuous use is 500 years.

As a practical example, if a customer has 28 three axis machines, the installed readhead population (p) is 84. The mean interval (t) between any readhead failure (ie n = 1) may be calculated by rearranging the MTBF formula:

$$t = \frac{Mn}{p} = \frac{500 \text{ years} * 1}{84} = \text{approximately 6 years}$$

Therefore with a total of 84 readheads running 24 hours per day, this customer could expect a single readhead failure approximately once every 6 years.

This information is not a guarantee of product reliability and does not represent a condition of warranty

(2) High-Performance system for data acquisition & processing

AIS2100 has higher capability of data processing than other measuring instrument. It adopted 16 bit processing method that is the level higher .than 12 bit processing one being used for ordinary sensor and data processing. Thus the capability of load analysis has increased by 10 times or more than other equipment, and it has been upgraded as the instrument that can evaluate fracture toughness and residual stress with its depth sensor. Furthermore, it could minimize distortion of the final result due to defective data by increasing the data acquisition rate more than 100 points per second.

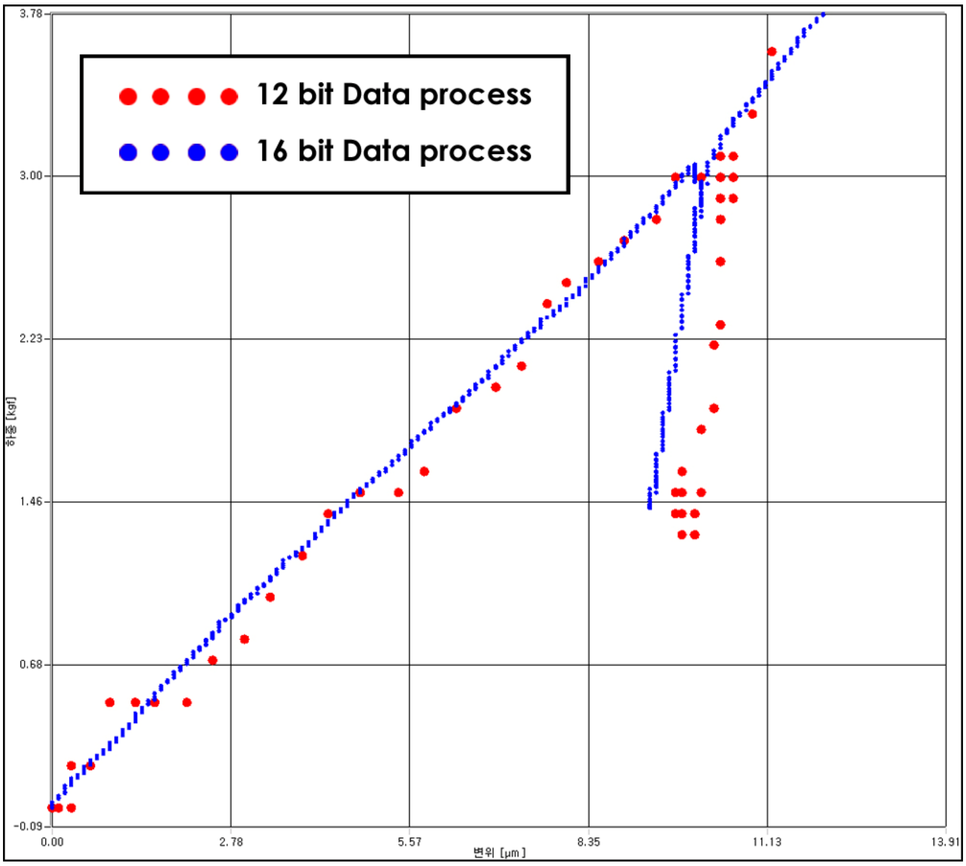


Table.2 Comparison of major specification

	Other equipment	AIS2100
Data process	12 bit = 2^{12} = 4096	16 bit = 2^{16} = 65536
Load resolution	100 gf (Max. 500 kgf)	7.6 gf (Max. 500 kgf)
Depth resolution	0.2 um	0.1 um
Data acquisition rate	10 points/sec	100 points/sec

(3) Self calibration tool

AIS2100 includes a self calibration tool. Ordinary measurement equipment requires periodic inspection and calibration in order to secure reliability, and such processes should be performed by a professional. As for AIS2100, checking state of the equipment can be done by inspection method, and calibration can be performed with the reserved self calibration tool, if required. Therefore the highly reliable data can be always acquired maintaining the best state.

Self calibration tool include various function needed equipment inspection & calibration.

- Inspection of load sensor
- Check and calibration of A/D
- Automatic calibration of AIS2100

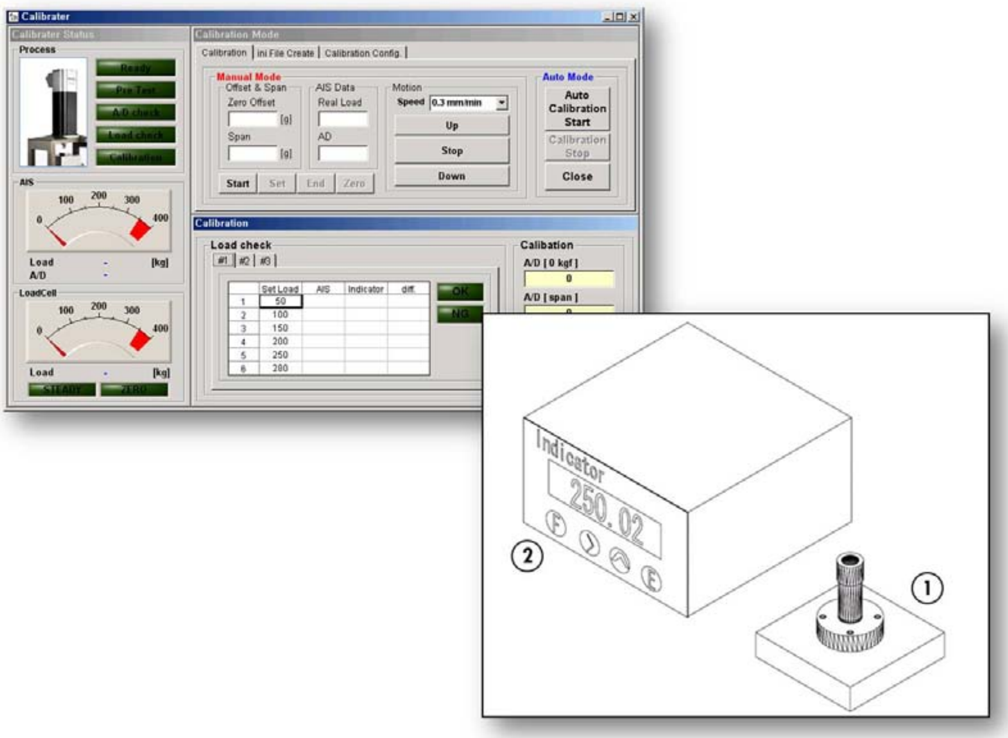


Table.3 Specification of calibration tool

Calibration load cell	Max. load: 500 kgf
Load indicator	Resolution 50 gf
Communication type	RS-232C
Control (Operating SW)	AIS Calibrator V1.0

(4) Compact hardware configuration

Measurement equipment of other companies consists of measurement processing hardware section, control box and data collection device (PC) that acquires and analyzes data. The issue to proceed with tests by this configuration is to secure the appropriate space.

AIS2100 minimized the configuration of equipment to solve the issues. Function of the control box is included in the main assembly utilizing embedded Mi-COM controller system technology, and software was configured to be directly controlled by PC. Besides, field test can be conducted without space restraint by minimizing communication and power cable.

Table.4 Comparison of major specification

	Other equipment	AIS2100
Composition	**3 PARTS** Head assembly Control box PC	**2 PARTS** Head assembly PC
Cable	**4 cables** Data communication cable Control cable Head assembly power cable Control box power cable	**2 cables or non-cable** Communication cable (Possible to Wireless module) Power cable (Possible to Private Battery)
Control type	**PLC type**	**MI-COM system type**

(5) Optimized attachments (Basic item)

Power plants and oil refinery facilities consist of variously shaped parts such as rotor, shaft, valve, casing, pipe and etc. Optimized attachments (jig & fixtures) should be applied to test equipment to meet these parts. AIS2100 is equipped with optimized attachments based on our field experience for more than a decade.

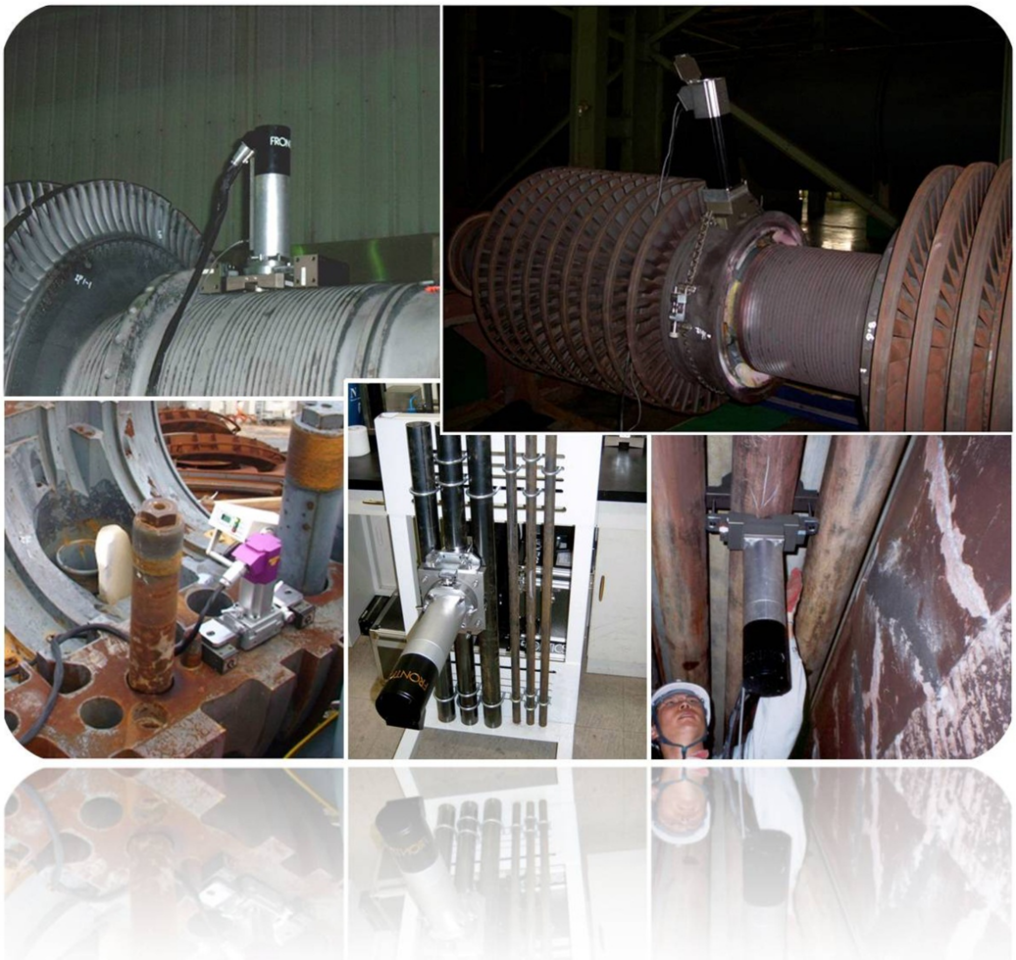


Table.5 Specification of optimized attachments

Attachment	Subject
V-block System	3/4 ~ 2 inch tube & bar (w/ Mico Fin-tube)
U-block System	3 ~ 6 inch pipe & shaft
Curvature magnet System	10 ~ 20 inch pipe / 20 ~ 48 inch pipe, shaft & rotor
Chain System	8 ~ 50 inch pipe, shaft & rotor
Flat magnet System	Plate, bridge & steel sheet

All products can be made to order.

<V-block system>

Components

Application

<U-block system>

Components

Application

<Curvature magnet system>

Components

Application

<Chain system>

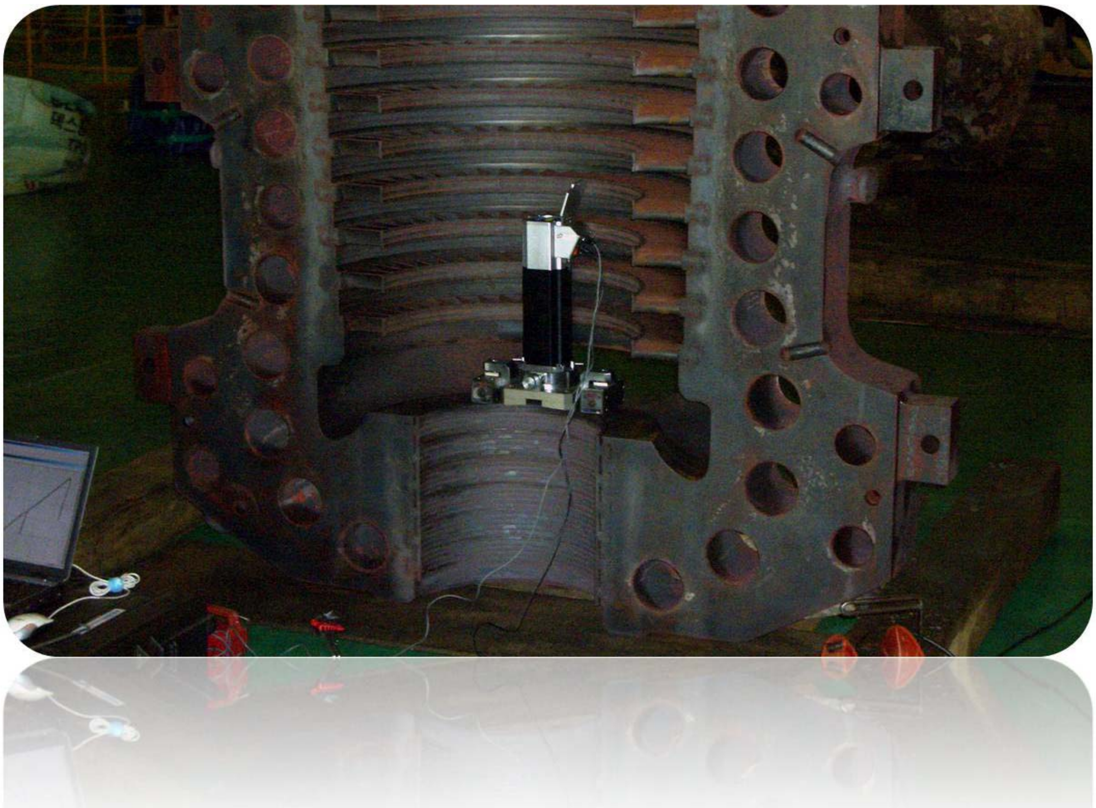
Components

Application

<Flat magnet system>

Components

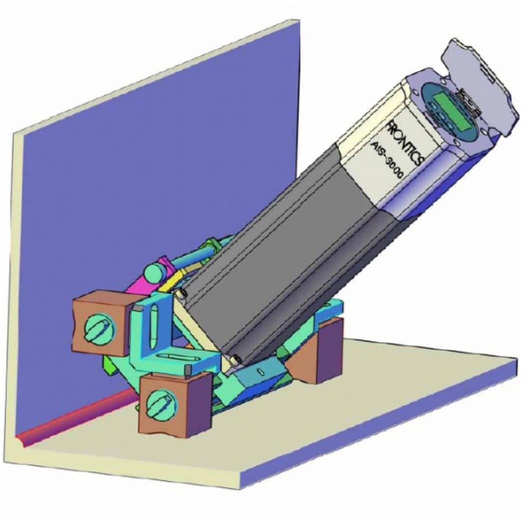
Application



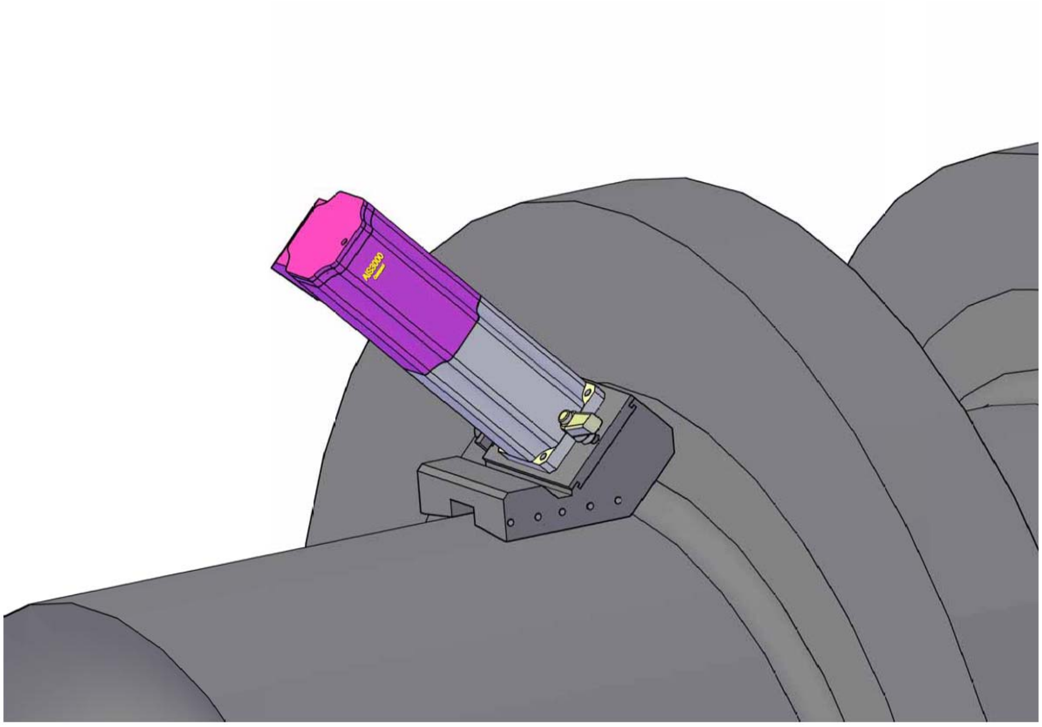
(7) Optimized attachments (Special item)

FRONTICS has attachments that enable tests in various shapes based on its field experiences during last 10 years or longer. Its design team designs and manufactures the exclusive attachments of specific targets, supplies and provides services to users. Following is the typical attachments:

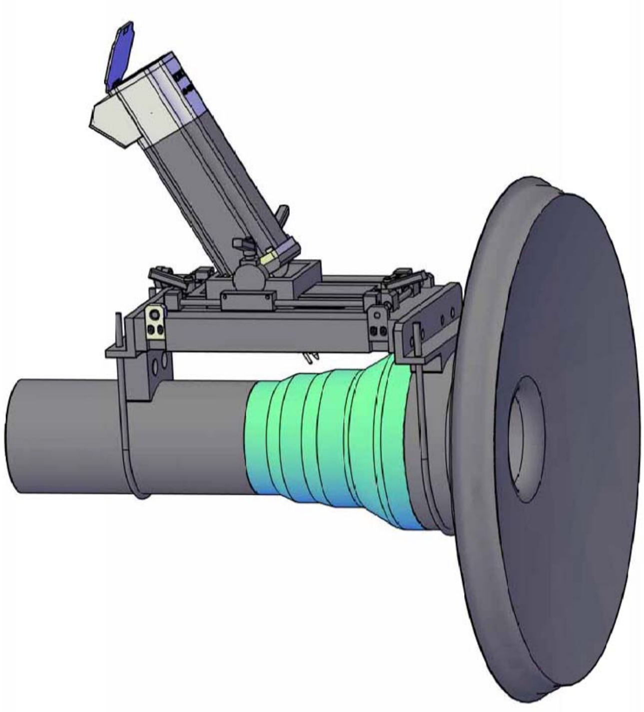
- **Attachment for Fillet Weldment**



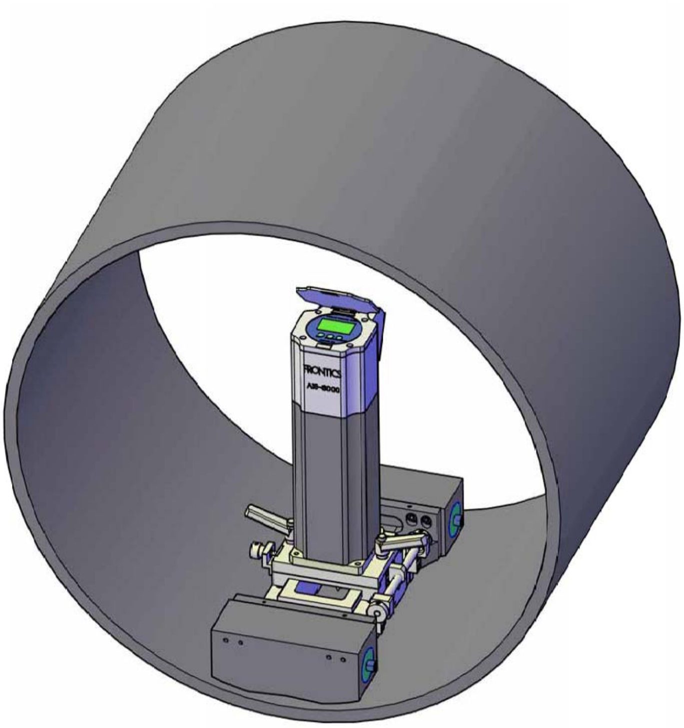
- **Attachment for Groove (Case of HP section in turbine rotor)**



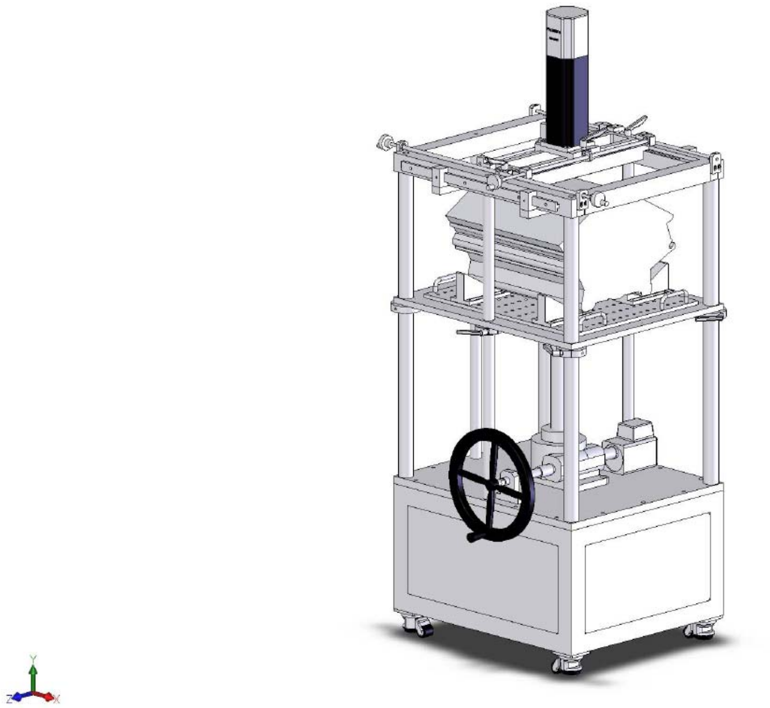
- **Attachment for steam vessel nozzle (Case of power plant facility in Korea)**



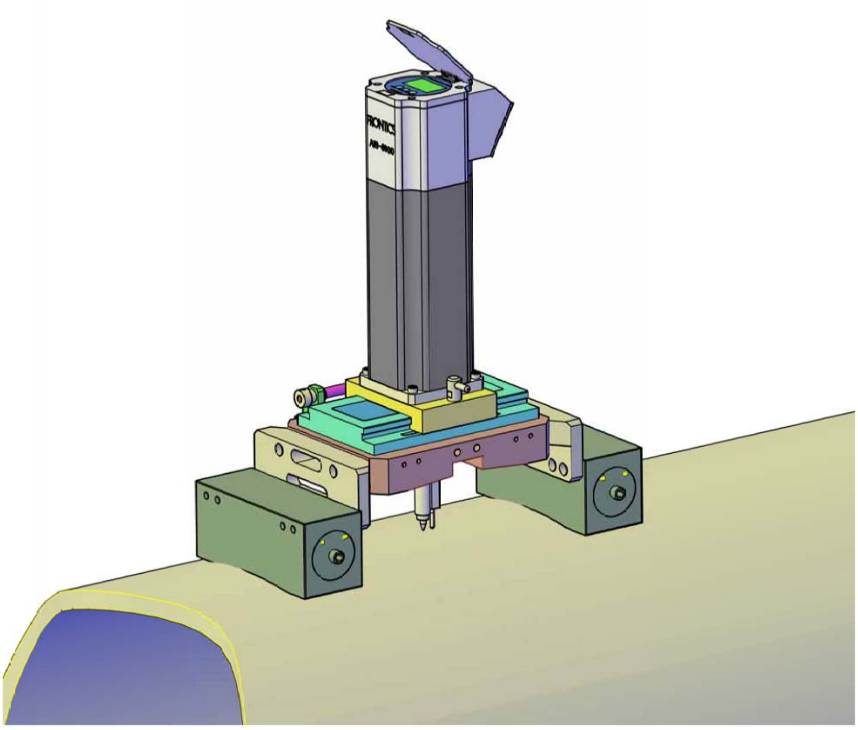
- **Attachment for Inner diameter of vessel & pipe (Case for KOGAS)**



- **Attachment for car engine (Case of automobile company in Korea)**



- **Attachment for high temperature pipe of nuclear power plant (Case of oil refinery in Korea)**



(7) Portable battery system

AIS2100 can be used in the environment free voltage (AC110V~220V). And it possesses reserved Portable battery system in case of difficulty in supplying power at a job site. The equipment can be used for up to 10 hours at the area where electric power is not available, and it is easy to use the system in the fields due to the lightweight of 2.5 kg that is merely one tenth of the existing UPS.

Table.6 Specification of portable battery system

Charge	220V AC
Output	24V DC, 10A
Size	195 x 80 x 140 mm
Weight	2.5 kg
Operating time	10 hours

(8) Wireless communication by Bluetooth module

AIS2100 has 2 sorts of communication system. Basically, high-speed USB communication is provided by RS-422 mode and the other one is wireless communication which is available by Bluetooth module. There is no need to use cable between equipment and PC (analyzing notebook) and to maximize a carrying and convenience as extending the field of operations and movements through the wireless communication, Bluetooth. AIS2100 maximize a carrying and convenience through the wireless communication module (Bluetooth module). Bluetooth module of AIS2100 is 30 meters of wireless transmits distance by default. Transmit distance can be extended using optional antennas. Software-free configuration supports using DIP-Switch and pairing button. It use RFCOMM, L2CAP and SDP protocol, and it has a FCC, CE, MIC and TELEC certification.

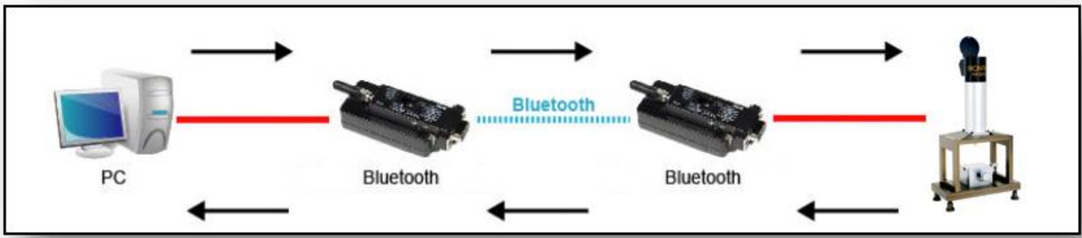


Table.7 Specification of Bluetooth module

CPU	RS232, Female DB9, 1200 bps ~ 230 Kbps CTS/RTS flow control: Default DTR/DSR for loop-back & full transfer
Bluetooth interface	Bluetooth v1.2 Class 1 Protocols - RFCOMM, L2CAP, SDP Working distance Default Antenna - Default Antenna 100 meters Patch Antenna -Patch Antenna 1,000 meters
Environmental	Operating temperature: -10'C to 55'C Humidity: 90% Non-condensing
MTBF	121.74 Years
Regulatory Approvals	FCC Part 15 Subpart C Section 15.247 FCC Part 15 Subpart B ETSI EN 300 328 / ETSI EN 301 489-1 / ETSI EN 301 489-17 EN61000-3-2, EN61000-3-3 / EN60950-1 MIC / TELEC
SIG QDID	B012393

(9) Portable grinder (Essential tool)

In the experimental stage of the AIS2100, The first step is securing illumination of the surface for testing subjects. There is a problem that it doesn't secure illumination, because existing equipment in front of a typical grinder equipped with a sand paper and use the method be applied generally. If the test is not meant to secure the necessary illumination, Normal load-depth data analysis has been unable to get the results will affect the analyzing results. In order to minimize problems on these tests, we provides only a portable grinder for the indentation test

Feature
- High precision, Lightweight, High reliability, Compact size motor
- Carbon brush motor is possible to operate 3 times longer than general motor
- RPM variation is minimal even when load changes
- Provides superior quietness from low speed to high speed and stepless speed control
- Possible to use interior battery (4 hrs in a charge)

Table.8 Specification of portable grinder [FPG-300]

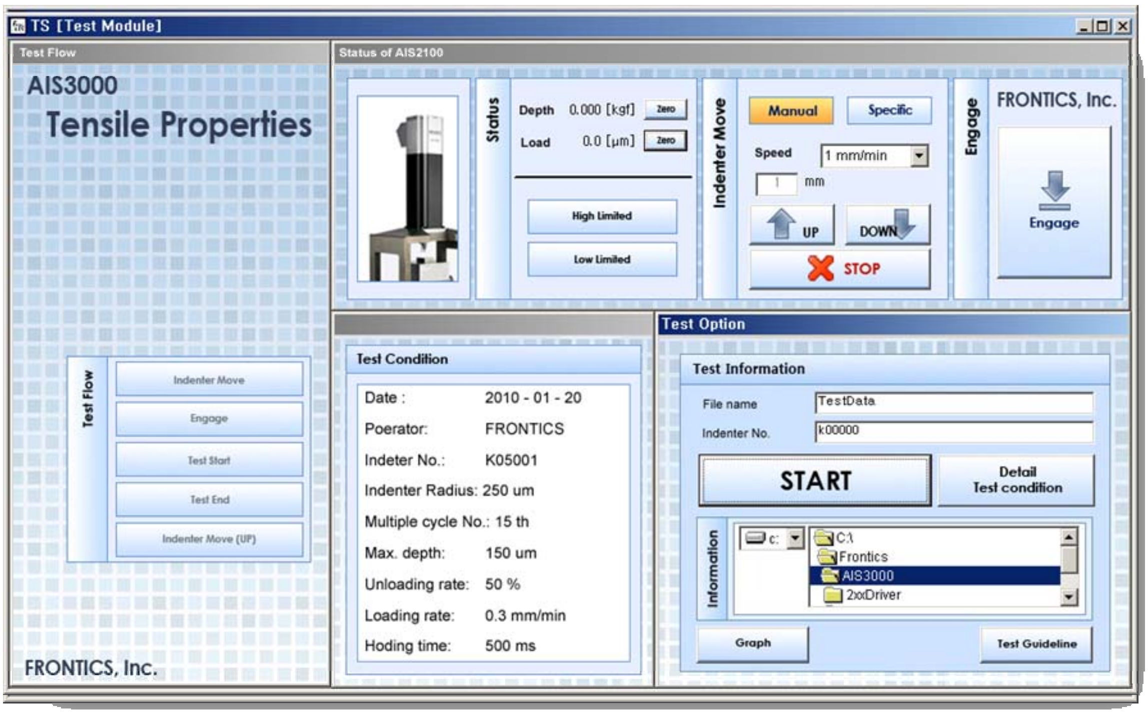
Speed	1000 ~ 25,000 rpm
Max. Torque	4.1 cN•m (420gf•m)
Size / weight	170 x 210 x 70 (mm) / 2.5 kg
Charge	24V DC, 2A (using Adapter)
Output	24V DC
Operating time	4 hours
Rubber disk size	Diameter 30 mm

4. Powerful Software

(1) AIS2100 V3.0 of device system

AIS2100 V3.0 of FROTNICS is the new concept software of a device type. It has been developed to process the data base of the result as well as test, analysis and reporting, from software processing test only in order to enhance users' convenience since the initial introduction in 2000. Furthermore, it is available to mount the fracture toughness module, which is the new measuring item, and residual stress module if required, through introduction of the concept of device. And it is also possible to add the device of special type tests (high/low temperature environment test, underwater environment test and so on) upon users' request.

It is configured to perform the dual system of test and analysis, that is so called the most difficult issue of measurement instrument, and it can provide more reliable test result by adopting the technique of test and analysis of ISO/TR29381 - international standard.



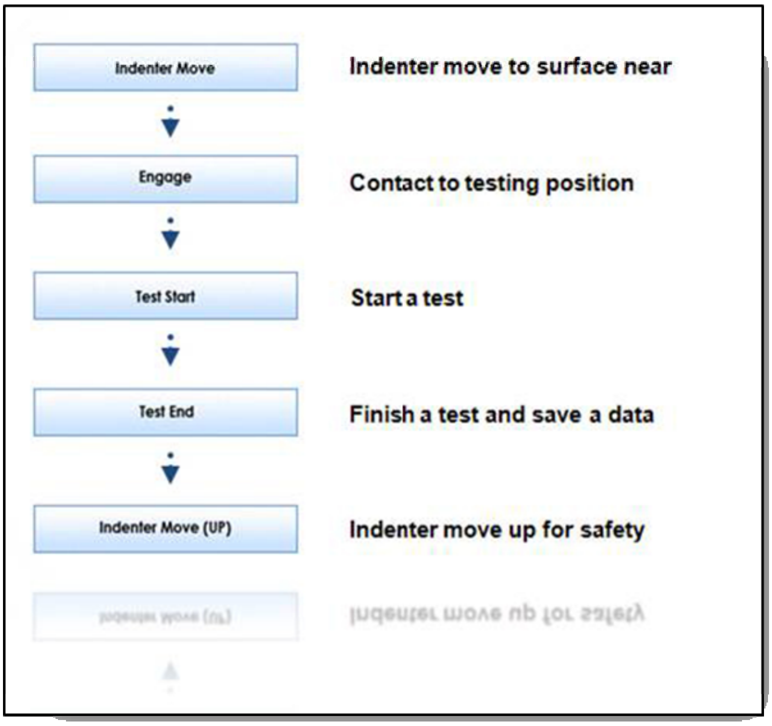
AIS2100 V3.0 Software

(2) Device configuration method and strong points

It is available to add simply to AIS2100 V3.0 fracture toughness, special environment and items required by users upon request, with the evaluation of tensile property as the basic item. And it is the device type software which various evaluation items can be added later. One of the most important features of AIS2100 V3.0 is being upgraded to evaluate diverse items with single equipment. It has minimized the inconvenience of the management of V2.0 to use the separate software per evaluation items respectively, and can be used, without purchasing the additional equipment, just by adding the software of new items later.

(3) Simplified operation

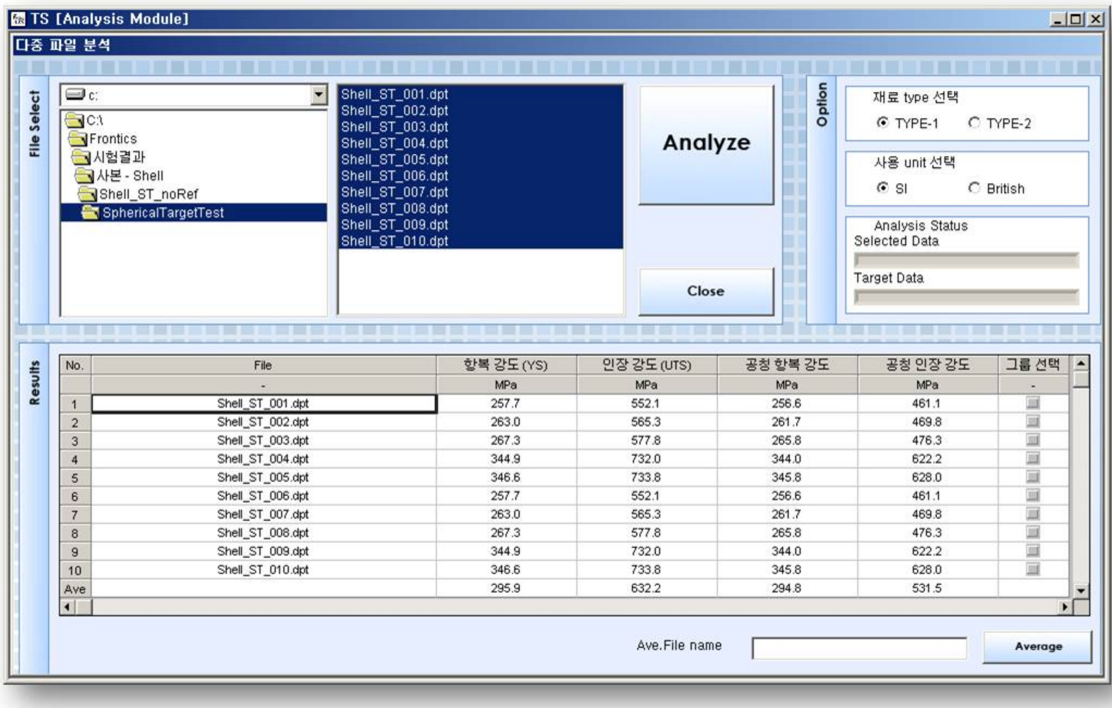
AIS2100 V3.0 has minimized the distinction of test steps and options adopted in AIS2100 V2.0. It has reduced the existing 6 steps to 5 steps of test process by eliminating a step.



Users can check 5 steps, and it minimized the error due to poor acquaintance of a test step by controlling to prevent from exceeding a step of software. And it deleted setting of the unnecessary option, enabling users to handle it with ease by changing the screen configuration to familiar drawings.

(4) Rapid analysis

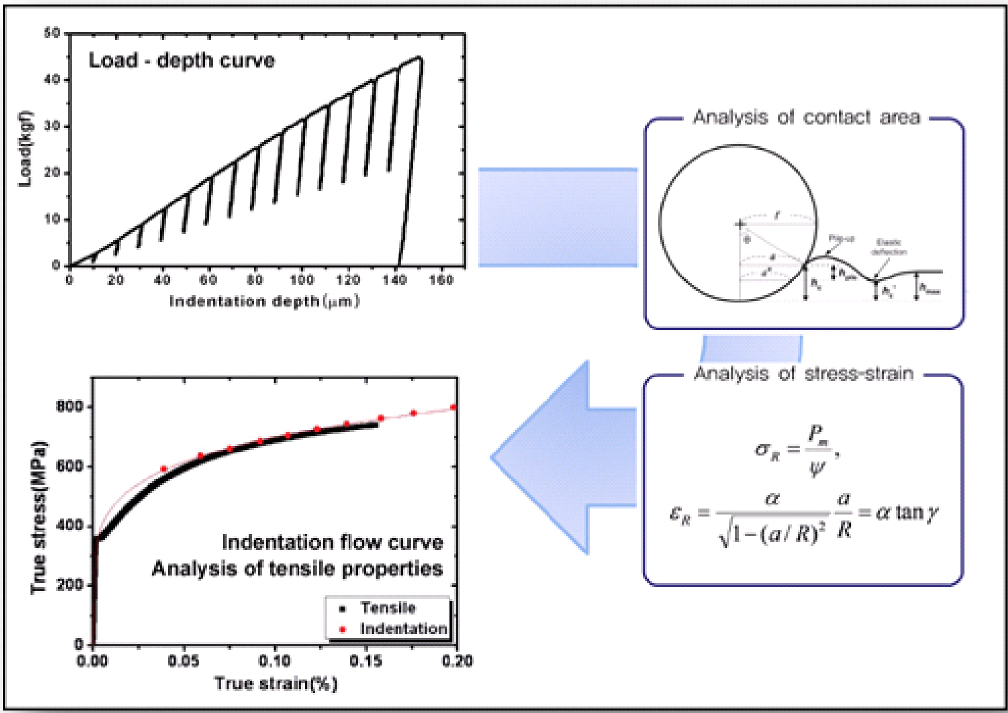
Multiple file analysis is available at AIS2100 V3.0. In the event that 10 tests are to be performed to a target subject, AIS2100 V3.0 can process it only once through the multiple file analysis, while the conventional software should perform the individual analyses respectively. Analysis result can be confirmed immediately, and the averaging function to combine the analysis results into one is included as well. And the option is so minimized that setting for analysis is limited to type of the test subject and unit only. All the processes of analysis will be completed by bringing analysis data, determining type and pressing analysis button. The result is kept in the form of text that can be used for reporting in the future, and this analysis technology can proceed without any critical issue in terms of reliability, as it follows ISO/TR29381 international standard



(5) Analysis method base on IIT (Instrumented Indentation Technique)

IIT was established as Korean Industrial Standard in 2002, Korea Electric Power Industry Code (KEPIC) in 2007 and finally advanced to ISO/TR in 2008. It receives lots of interests throughout the world owing to be certified as ISO. And IIT which is based on international ISO/TR29381 was applied to AIS2100 V3.0. And then

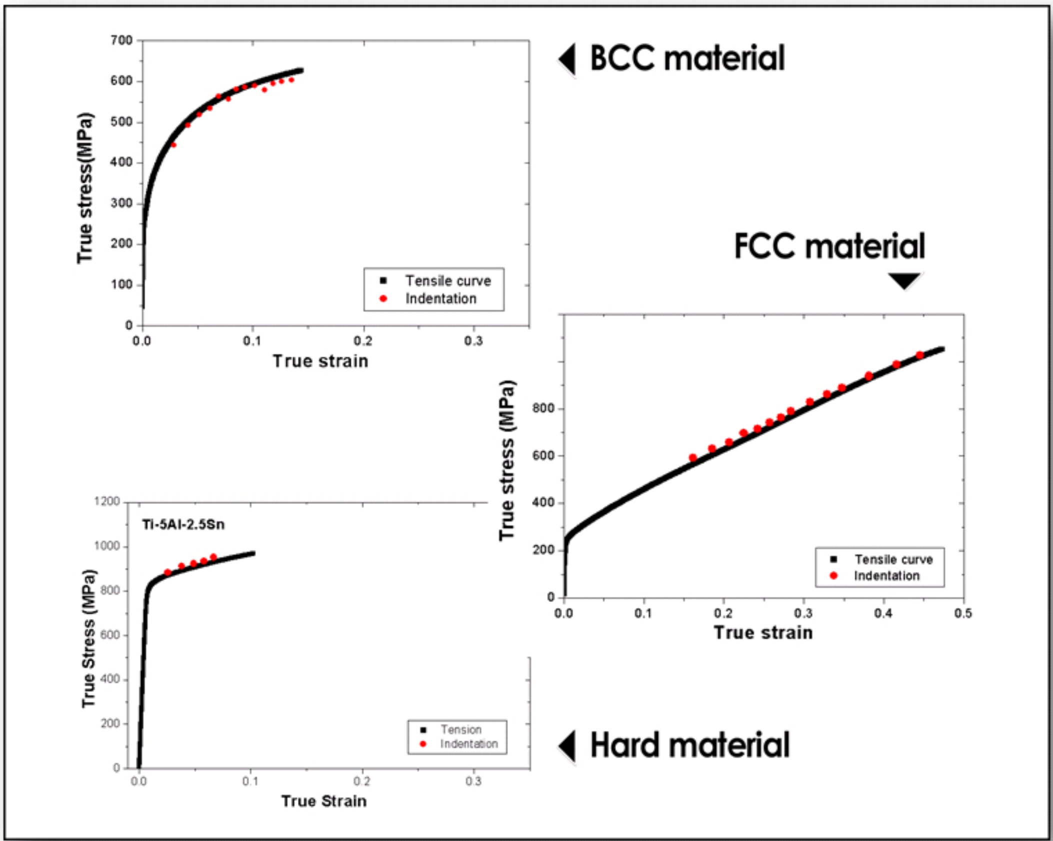
Properties analysis of AIS2100 V3.0 can be applicable to the range of most of metals including ordinary carbon steel, aluminum alloy, SUS and high strength steel. It is divided into basic 3 groups (Type I, Type II and Type III) and the additional group (Type IV) to increase the accuracy of the result. It is possible to test subjects without putting damage in the field, since pressure is added to the depth of only 150um by instrumented indentation test method. And beginners can proceed easily and fast with the test due to simple preparation process and test.



(6)Targeted to various materials

Property evaluation items of AIS2100 V3.0 have been expanded and simplified. Evaluation items that are available by AIS2100 V3.0 include metal material of BCC structure (Type I), SUS series of FCC structure (Type II) and metallic materials of high strength steel (Type III) and so on, except nonmetallic materials. And it is also available to add the exclusive analysis method of the material that users commonly use.

Analysis subjects are divided into Type I, Type II and Type III for analysis. It would be most convenient for users to evaluate subjects without dividing them, however, subjects are divided into 3 types in order to secure higher accuracy and reliability of the analysis result. Classification of type can be performed easily by test engineers in charge, and beginners can distinguish it and divide into Type I or Type II with a magnet.

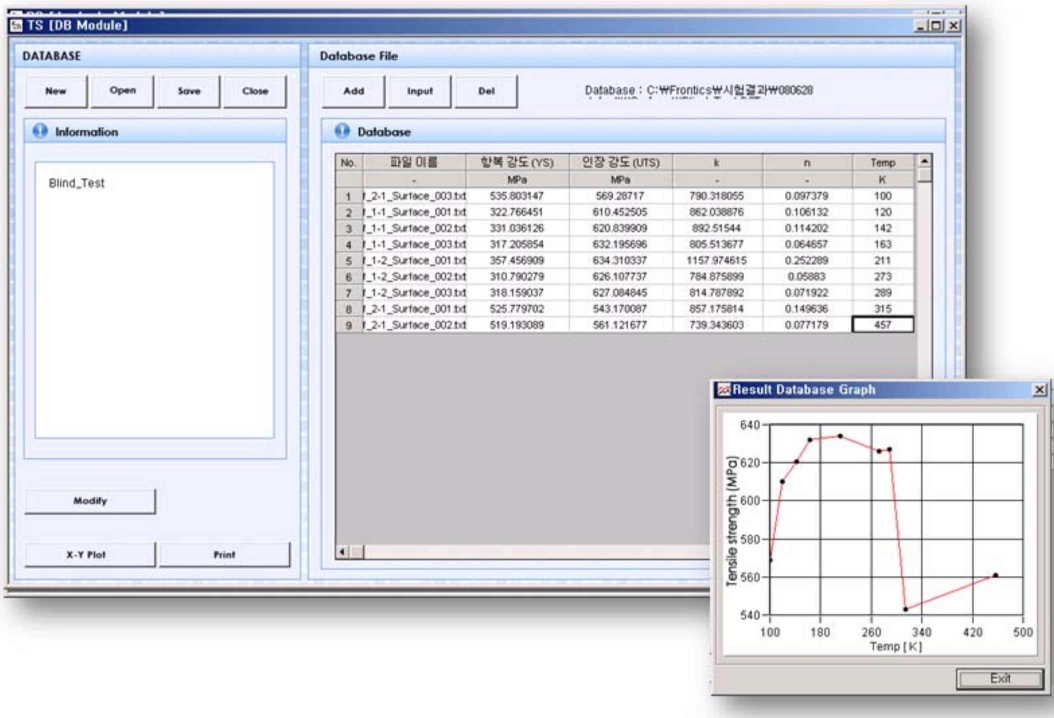


(7) Useful function for data analysis

Database function has been added to AIS2100 V3.0. Test results can be stored with the test field conditions, and the changing status can be compared according to criteria.

A lot of equipment suppliers attempt to create such database, however, it is inconvenient to manage a number of software with unnecessary works, since the numerical evaluation result of items should be organized and DB processed. As for AIS2100 V3.0, added the function of database of the result at the same time with the analysis, and unnecessary uses and works of software can be minimized by insertion of the additional condition together with the contents in the test result.

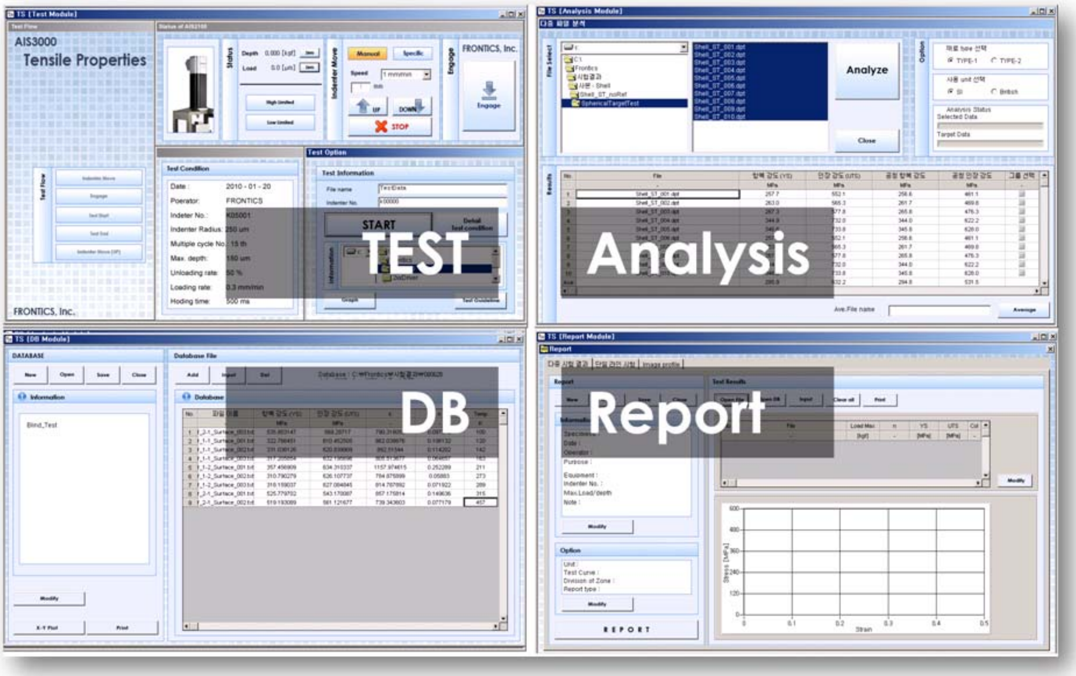
Basic form of database is included in AIS2100 V3.0. The form of database can be amended and changed upon user's request, that can be used as own database of users by providing as the form of device.



(8) All–in–One Software

AIS2100 V3.0 is All-in-One software that achieves test, analysis, database and reporting. It has been developed for field users to access easily by minimizing the operation of users, securing the speed at site to process lots of test data simultaneously.

Furthermore, it added the new feature to make reports and database of analysis results in single software. In case of the software included in the existing measurement equipment, the practical utilization of the test result varies by user's ability, since it shows only raw data in small scale and test results only in large scale after testing. But AIS2100 V3.0 has resolved all the issues by processing them in single software. AIS2100 V3.0 is moving forward to the primary goal of AIS Software series - Easy, Fast and Powerful Software.



5. Test Flow

(1) Test preparation

You have to perform preliminary test planning for a specimen before you carry out a test. Depending on the shape and location of a specimen, you have to select the appropriate attachment as well as jig and vise. If a specimen is in a working site, you have to ensure if it's feasible to secure a testing location, determine which attachment you are going to use and select a testing location to obtain the data for analysis. In addition, even if you perform a test in a lab, you have to select different attachments, jigs and vises depending on whether it holds a block shape or maintains its original shape.

a. Selecting testing location

In working sites, a testing location is determined by the dovetail slider that is combined with the main body. There are much less restraints in selecting testing locations for tests performed in labs compared to those performed in working sites. When you use MPS or RS-MPS instead of attachment, you can perform a test within the size range of Stage. When you determine the testing location you should first consult with the test requester. The testing location should conform to the testing purpose and the following agenda should be mutually discussed.

- The testing indentation should at least 2.5mm, preferably 3mm or more.
- The indentation depth should be at least 3mm, preferably 10mm or more.
- You should select a location to ensure at least three sets of effective data in order to secure reliability.
- In case of the weld zone on which you can perform only a single test, you are likely to get data that are not very reliable.
- The heat affected zone of heterogeneous materials welding may create variations.
- Materials with coating layers may result in an inaccurate test.

b. Securing the Surface Roughness

The next important thing to do right after a test planning is complete and a testing location is determined is to secure the surface. The depth used in a test ranges from 0.15 to 0.25 so if foreign matter sits on the surface or illumination is not intense enough, it is difficult to obtain precise data and also you are likely to create errors in analysis result. For this reason, securing the appropriate surface roughness greatly affects the final result.

- Reason of securing surface roughness

There are two different size indenters used in a test, which are the 0.5mm indenter and the 1.0mm indenter and if the surface roughness is poor you are likely to get bad data, thereby impairing reliability of the test result. If a surface roughness is unstable or an emery paper with less abrasiveness is used the first contact area with an indenter may be with the sides of an indenter instead of the head. Then, you are most likely get the bad curve in the load-depth curve due to the initial load reduction. Therefore, you should secure the recommended amount of light intensity as well as sufficient testing space in order to obtain reliable data.

- Standard surface roughness

The polishing is prerequisite to carry out a test. Specifications are as follows.

- The minimum space for polishing is 10 x 20 mm (space for 3 to 5 tests)
- The depth for polishing is limited to 0.3mm through 2.0mm
- Minimum surface luminous intensity: Sand paper No. 400
- Recommended surface luminous intensity: Sand paper No.600 or higher

c. Selecting attachment

You should check the shape and characteristics of a specimen before you determine an attachment. Specimens applicable to each attachment are as follows.

d. Amalgamation of an Attachment

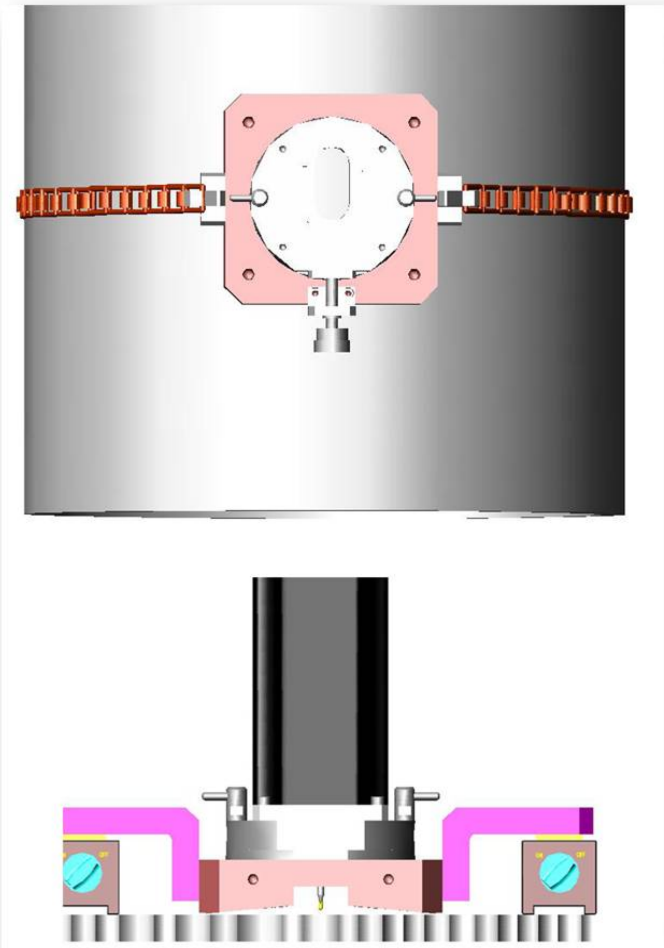
Upon completion of determining an appropriate attachment you should amalgamate, starting from an attachment. If you combine the equipment first with an attachment you will have some difficulty in combining with actual specimens later on so you should amalgamate the main body after amalgamating an attachment. Refer to the ‘how to amalgamate an attachment’ for details.

e. Amalgamation of Main assembly

After amalgamating an attachment, you need to amalgamate the main assembly as the last step. You should be careful not to allow the indentation module to collide with a specimen.

f. Verifying test location

If combination of equipment is complete you should verify the test location through test operation. It is recommended that you move the indentation module close to the specimen to check if it fits in the test location, rather than just verify it with naked eyes.



(2) Test – flow to tensile properties test

a. Movement of indentation module

The indentation testing begins with the movement of the indentation module. First, move the indentation module that contains weight sensor, proximity sensor and the indenter close to a test object. The proximity sensor must be in contact with a specimen and the weight sensor must be close enough to be within the distance range of 4mm. You can use the automatic movement if you know the distance between an indenter and a specimen and also select the manual movement in case of performing a virgin test or without knowledge of distance.

b. Engage

You can perform Engage when you get an indenter close to a specimen. The Engage is the function that allows an indenter to get into contact with a specimen. When you perform it in the manual mode, an indenter may collide with a specimen instead of contacting it, leading to an unplanned halt of a test. If the Engage phase proceeds normally, an indenter moves downward at the same speed as that during the test and stops when it comes into contact with a specimen.

c. Start test

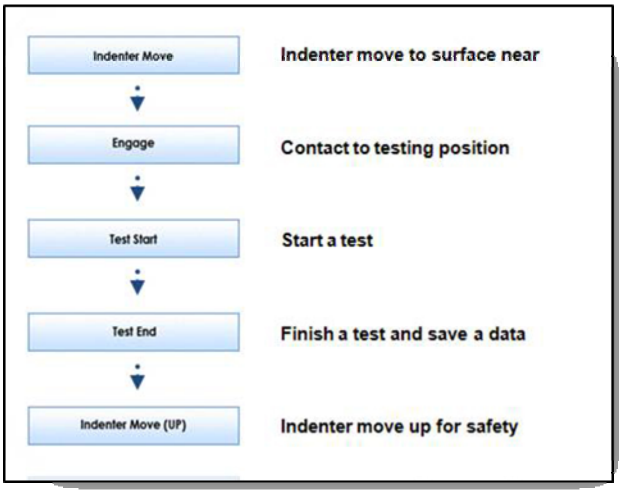
You don't have to manually configure testing conditions in the AIS2100 software. A set of optimal testing conditions are predetermined through years of R&D and hands-on experiences. All you have to configure is the size of an indenter. After verifying that, you can now determine a folder to save a test file in and the name of the file before executing a test.

d. End Test

Upon executing a test, you can verify the load-depth data in real time. You will obtain testing data through repeated loading/ unloading depending on testing conditions and upon completion of the test, data are automatically saved. All you have to do after that is to check if there's any error in the test and when it comes to errors in curves, refer to the troubleshooting manual.

e. Movement of indentation module

Upon completion of acquisition and save of testing data, an indenter movement window appears. An indenter will remain in contact with the surface of a testing object even after the test is complete. If you move the indenter in this state it will cause damage not only on the testing object but also on the indenter itself. So, you have to move the indenter away from the testing object upon completion of the test.



(3) Analysis

You can execute this function either by clicking File>Multiple File Analysis on top menu or by clicking multiple data icon.

a. Open the File

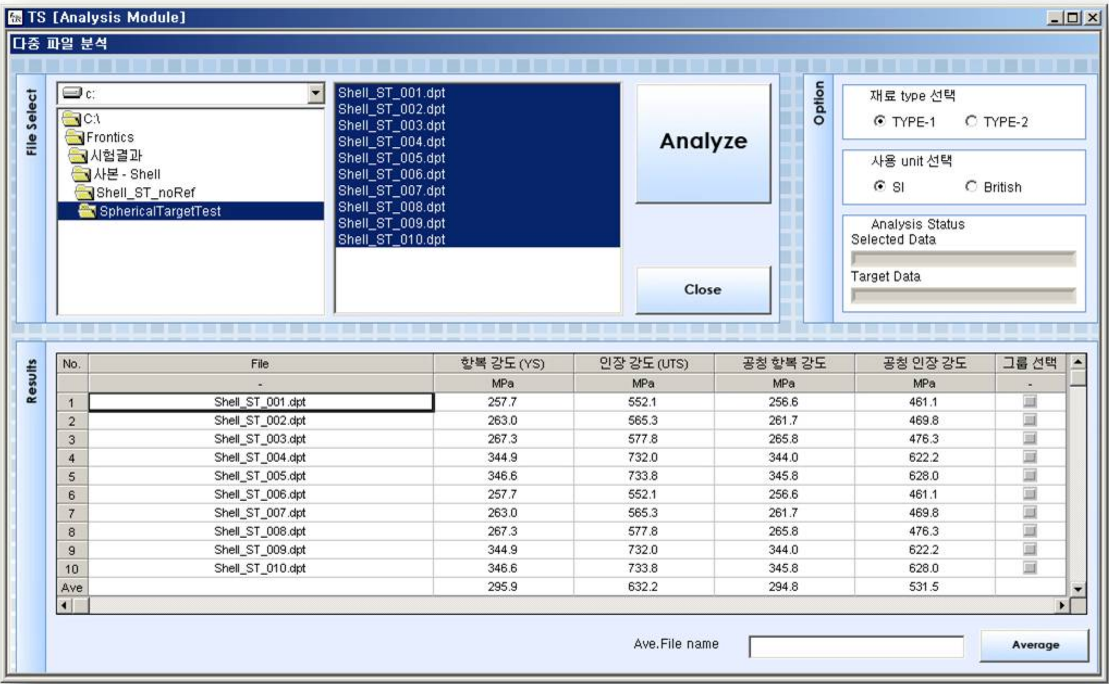
On the top left corner of the multiple data analysis module is the window to select the file for analysis. This one is similar to the window to open individual data file but is different in terms of the selecting method. Just like in Windows file explorer, you can make multiple selections with drag and drop or using Ctrl key. This is how you complete selecting files.

b. Select the Analysis Option

There is an analysis option on the right side of the file open window. As described above, you can select the analysis method and the unit of analysis result here. You can select either FCC or BCC and the unit to be used in the result as well before executing analysis.

c. Result Analysis

If you execute analysis using the multiple data analysis module, you can verify the result immediately on bottom. The result values are shown in unit you selected along with the average value of analysis result upon completion of analysis. The analysis result can also be directly linked to the report module, which will be described later.



(4) Completing Test

Upon completion of a test, disassemble equipment as well as software in the order described below.

a. Terminating software

The first thing to do upon completion of a test is to terminate the software. Since the AIS software communicates with the equipment through the USB, it might be damaged due to abrupt disconnection from the equipment. Therefore, you must terminate the software as soon as the test is completed.
You can terminate by clicking 'File > Close'. If you forcefully terminate the software by clicking 'x' mark on the top right corner of the window, it might cause an abnormal USB disconnection from the equipment, spawning unexpected problems later on.

b. Removing connection

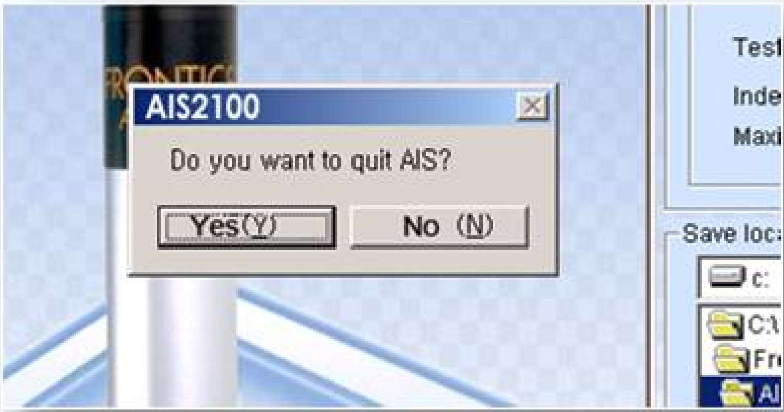
If you terminate the software, turn off the power supply of the equipment, followed by removing connection cable between a PC for analysis and the equipment. This phase can be performed differently in labs and in working sites. In labs, you can just disconnect the receiver attached to the PC. However, in working sites, you have to remove both the receiver and the cable in order to prevent the possible damage on the connector.

c. Disassembly of equipment

Disassembly is the opposite the installation in terms of order and direction. Separate an attachment from the main assembly and remove the indenter. After removing an attachment, keep the dovetail-slider and the main assembly recombined for safety purposes.

e. Treating test surface

If disassembly of equipment is complete you should treat the surface of tested area. If a specimen is coated in accordance with a certain standard, you have to apply the same coating. Even without the presence of special treatment, you should at least remove water and impurities from the surface and to take a corrosion-preventing treatment in order to keep it from being corroded.



6. Specification of AIS2100 (Typical series)

Model		AIS2100
Size (weight)		100x100x354 mm (7 kg)
Max. load		500 kgf
Resolution (Load / Depth)		7.6 gf / 0.1 um
Full stroke		40 mm
Loading rate		0.05 ~ 30 mm/min
Communication		RS-422/ Wireless module
Data acquisition rate		100 point/sec
Power	Adapter	AC 110~220V (free voltage)
	Battery	Portable battery (10hrs in a charge)
Analyzing computer	Standard	Laptop PC (w/SW)
	Special	Rugged Computer (Optional)
Indenter		Tungsten Carbide (WC) spherical indenter Basic - Dia. 0.5 / 1.0 mm
		Optional – Dia. 0.25 / 0.51 / 0.76 / 1.56 mm Vickers, Brinell, Rockwell C Indenter
Attachment	Lab – type	Micro Positioning Stage (MPS) RS – MPS Swivel & vise of specimen
	Field - type	Curvature Magnet System Flat Magnet System Chain System U-block System V-block system

Standardization

1. Korean Standard & ISO/TR29381
2. Certification
3. Other international activities
4. Patents

1. Korean Standard & ISO/TR29381

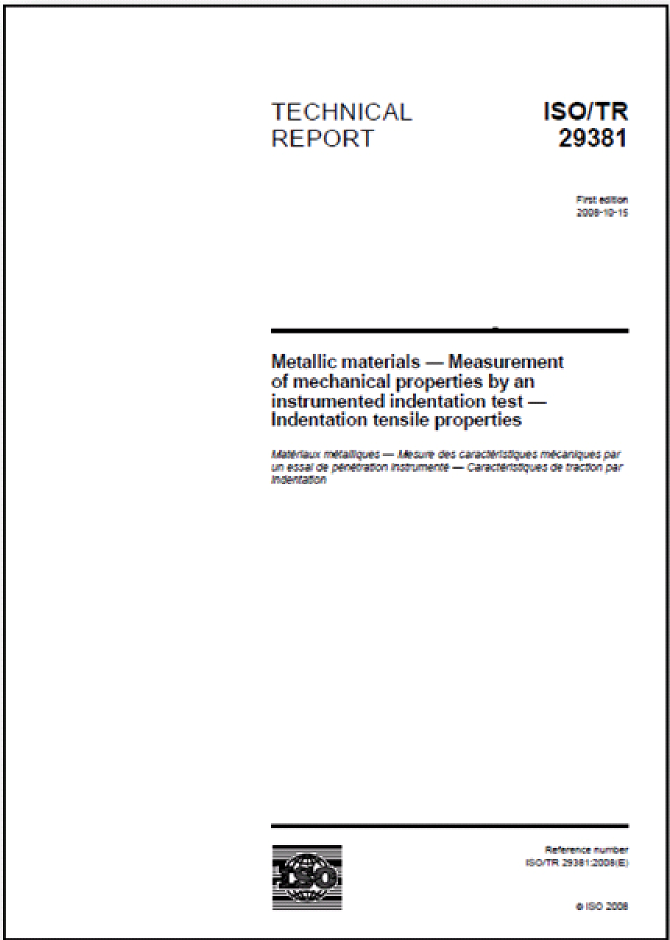
(1) Status of Establishing the Korean Industrial Standards (KS) of the Law on the Instrumented Indentation Technique

Two cases of the Korean Industrial Standards related to the instrumented indentation technique were established. KS B0950, 'Metallic Materials - Measurement of Indentation Tensile Properties by an Instrumented Indentation Test', was established in 2002, and KS B0951, 'Metallic Materials - Measurement of Welding Residual Stress by an Instrumented Indentation Test', was established in 2005.
These two standards are the national standards established the first in the nation in the related area.

(2) Status of Establishing the International Standards of the Instrumented Indentation Technique

The international standards ISO 14577-1, -2, and -3 related to the instrumented indentation technique were established in 2002, firstly in the world. In this standard, several environmental factors and the experiment method to be considered when performing the instrumented indentation test are well specified.

In the ISO TC164 meeting held in Spain in 2003, Dongil Kwon, Professor of Seoul National University and Technical Advisor of Frontics, first proposed the international standardization of KS B0950, 'Metallic Materials - Measurement of Indentation Tensile Properties by an Instrumented Indentation Test'. The agenda was selected as the official working item in the meeting in Beijing, China, in 2004, and the working group participated by seven countries such as Korea, England, Germany, USA, Japan, China, and Luxembourg was organized. Professor Dongil Kwon was appointed as the convenor. The international standardization of KS B0951, 'Metallic Materials - Measurement of Welding Residual Stress by an Instrumented Indentation Test', was proposed in the meeting in London, UK in 2005. The opinion of each country was collected to propose the integrated draft in the meeting in Seoul, Korea in 2006. Finally, ISO/TR29381, 'Metallic Materials - Measurement of Mechanical Properties by an Instrumented Indentation Test - Indentation Tensile Properties', was established as the international standard document in October 2008. ('Measurement of Residual Stress by Instrumented Indentation Test' is included as the annex.)


TECHNICAL REPORT

ISO/TR 29381

First edition
2008-10-15

Metallic materials — Measurement of mechanical properties by an instrumented indentation test — Indentation tensile properties

Matériaux métalliques — Mesure des caractéristiques mécaniques par un essai de pénétration instrumenté — Caractéristiques de traction par indentation

Reference number
ISO/TR 29381:2008(E)

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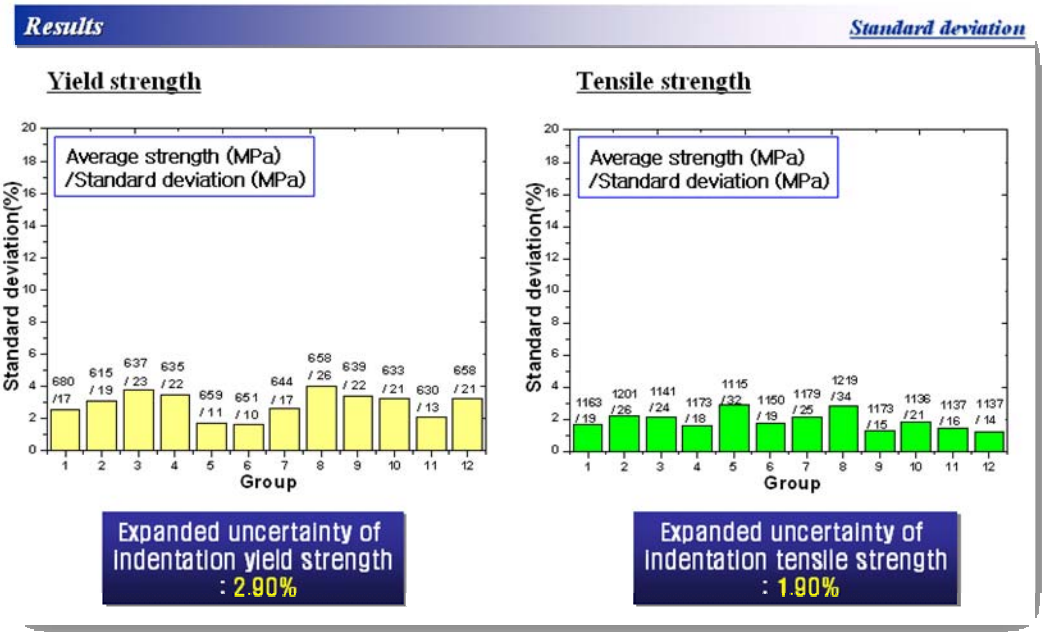
(3) International Standard Support Activities of FRONTICS, Inc.

The AIS2100 equipment of Frontics is based on the representative stress and strain method that is the first method of the international standard. The equipment of Frontics was used in the Round Robin Test (RRT) done during the process of establishing the standard and in the verification test on various metallic materials, and the repeatablility within 3% and the properties evaluation correctness within 5% compare to the tensile test were verified during the international standard establishment process.



(4) Claim of Mr. Haggag and the Official Response of ISO to It

As for ISO/TR29381 established and published as the international standard in October 2008, Mr. Haggag, Representative of ATC Corporation, stated that ISO/TR29381 plagiarized his own technology by e-mail in March 2009, raised an objection to ISO, and insisted that ISO/TR 29381 should be withdrawn. Especially, Mr. Haggag insisted that the terminology of ‘Instrumented Indentation Technique, IIT’ cannot be used as the terminology referring to the method to get the tensile properties with the indentation test and that only his ‘Automated Ball Indentation, ABI' should be used. Moreover, he asserts that the instrumented indentation technique is applied only in the nano scale and says that several techniques used during the indentation test are only their techniques. However, the experts on the instrumented indentation test from England, Germany, and USA refuted that Mr. Haggag’s assertion doesn’t make any sense. The instrumented indentation test is the general and inherent research field that has been studied by various researchers in the world since 1950s. The technique to get the load-depth curve by sensing the load and displacement in real time is called as the instrumented indentation technique worldwide (if Mr. Haggag is excluded) regardless of the macro, micro, and nano scales. Furthermore, several indentation techniques used by Mr. Haggag have been used by several researchers since 1970s and are based on the research details published as papers. In fact, there is none that can be Mr. Haggag's unique technique.

ISO flatly refused the preposterous Mr. Haggag's assertion by gathering the opinions from several experts from the world and awarded the validity as the international standard to ISO/TR29381 that is the tensile properties evaluation method with the instrumented indentation technique.

It is being used as the normal international standard through Mr. Haggag's assertion, experts' antagonistic opinions on it, and ISO's official response to it.

2. Certification

FRONTICS Inc. and AIS equipment got the certifications to be approved the reliability. We have secured reliability of the equipment with acquisition of certifications of various sensors and electronic components as well as international standard ISO9001 concerning quality management and quality assurance.

- ISO 9001
- Certification of Sensors
- Certification of the equipment

Safety	USA	FCC – Federal Communications commission HCT-F06-0101/HCT-F07-0708/ HCT-F09-0211
	EUROPE (EU)	CE–MARKING: Conformite Europeene EMI: HCT-C06-0802 EMS: HCT-C06-0802 RF: HCT-RF06-017 SAFETY: 13007219 001 SAFETY: IEC 61010-1 / EN 61010-1
	International	IECEE (CB Scheme) – IEC System for Conformity Testing and Certification of Electrical Equipment (DE 2-012230 / DE 2-012231)
	KOREA	MIC (Ministry of Information and Communication) EMC: AIS-AIS-3000Base / R-LARN8-05-0099
Reliability	KOREA	NET (New Excellent Technique) / NEP (New Excellent Product) / PPS (Excellent Product)

3. Other international activities

(1) FRONTICS activities for Mackenzie Gas Project

1) First contact from Canada (2004. 9)

→ Indentation testing issue
(Mackenzie Gas Project Field Weldability Trials
– Mechanical Testing Specification and Scope of Work)

2) Second contact to Canada (2004. 10)
→ Accept the testing issue in IPE2004
Mechanical testing specification and scope of work
Determination of Tensile Properties through Instrumented Indentation
- The client will provide the vendor with weld cross-section that are polished and etched for evaluation.
- Additional tests may be requested on a weld cross section.
- The yield strength, ultimate tensile strength and strain hardening coefficient shall be reported.
- The existence of a discontinuous stress strain curve, exhibiting a Luder's strains, shall be reported.
Determination of Fracture Toughness Properties through Instrumented Indentation
- The client will provide the vendor with weld cross-sections that are polished and etched for evaluation.
- Additional tests may be requested on a weld cross section.
- The tests shall be performed at the temperatures noted in the test scope document.
- The vendor shall report the estimated J1C value and the basis for the calculation.

(2) Co-works with TWI (The Welding Institute)

FRONTICS has been working with TWI in UK. The first TWI Core Research Project has been completed successfully in 2004 and now the second co-work is proceeding.
An article below is an extract from TWI magazine
(**Issue 133 November/December 2004)**

TWI Connect

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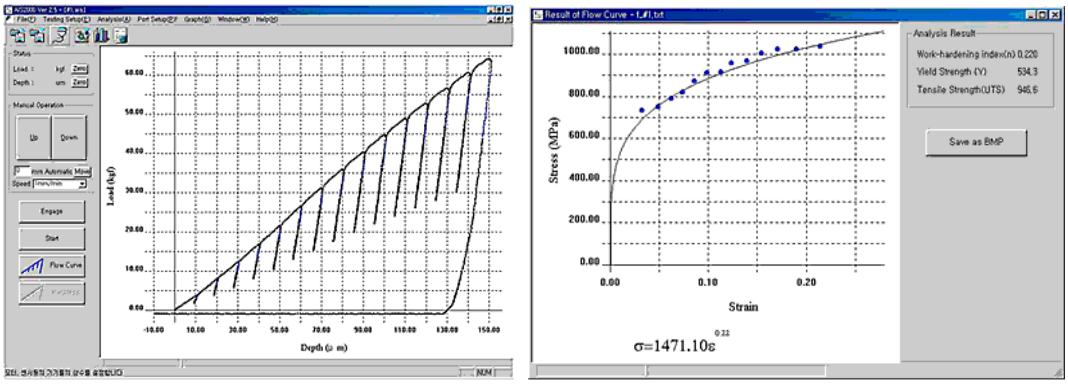
Mechanical testing made easy - top equipment at TWI
A ball indentation system, capable of determining the mechanical properties of any metallic substrate, has been loaned to TWI by Frontics of Korea. The AIS 2000, as it is designated, is to be used in a TWI Core Research Project on miniaturized mechanical testing. Frontics is one of the pioneers in manufacturing portable ball indenters, for *in-situ*/non-destructive evaluation of tensile properties and hardness. The system is light-weight and miniaturized for easy and fast transportation and installation. The indentation load-depth data can be converted to various tensile properties, through software installed in the data analyzing computer

The mechanical parameters that can be measured are as follows:

- Flow curve
- Yield strength
- Tensile strength
- Work hardening exponent
- Stress coefficient (K in the stress-strain correlation, $\sigma = K(\varepsilon)$)
- Vickers Hardness
- Rockwell Hardness A, C, D.
- Brinell Hardness (mini-ball)

Fig.1. AIS 2000 system

Fig.2. Load-depth curves and the stress-strain curve predicted



AIS 2000 applications can be divided into two categories:

In the lab it can....

- Evaluate tensile properties of materials under development, without the need for a standard/conventional tensile-test
- Compare strength characteristics of weld/heat-affected zone/base metal and local regions with microstructural gradients for qualification/research purposes
- Provide basic mechanical properties for finite element analysis of similar/dissimilar materials

Out in the field it can....

- evaluate mechanical properties of ageing structures and facilities using non-destructive and in-situ analysis
- evaluate degraded properties of power plant and oil and gas company facilities for fitness-for-service and life assessment studies
- control the quality of materials and processed metal in cars, ships, trains and aircraft

Fig.3. Examples of in-field application of AIS 2000 system

To find out more on TWI development of automated ball indentation procedures and miniaturised mechanical testing contact Afshin Motarjemi E-mail: afshin.motarjemi@twi.co.uk

PROJECT OUTLINE

TWI

WORLD CENTRE FOR MATERIALS JOINING TECHNOLOGY

PR10239 JUNE 2006

Assessment of Ageing Structures Containing Defects Using A Non-Destructive Indentation Technique

For: A Group of Sponsors

SUMMARY

Mechanical properties of structures/components (pipelines, boilers, reactors and other welded structures) in oil and gas, power and petrochemical industries suffer from ageing and therefore their integrity and safe in-service operation could be questionable. To monitor this phenomenon effectively, local properties of structures/component need to be recorded at specified intervals. Ideally this should be conducted without affecting the service operation of the structure/component by means of a non-destructive technique. A test programme using the instrumented indentation technique (IIT) is proposed to verify the capability of the technique for non-destructive determination of the local mechanical properties including tensile properties, fracture toughness and surface residual stress of aged welded components.

概要

石油、ガス、電力、石油化学業界で使用されている構造物や機器（パイプライン、ボイラー、反応機器他溶接構造物）の機械的特性は老朽化により健全性と安全性が疑問視されます。かような現象を効率的に監視するには、構造物や機器の局部的な特性を定期的に記録する必要があり、この場合、操業に影響を与えない非破壊的な方法で行う事が理想です。そこで老朽化した溶接構造物の強度、堅牢性、表面残留応力といった局部的な機械特性を「Instrumented Indentation Technique (IIT)」を用い非破壊的に監視する方法を実証する為のテストプログラムを提案します。

BACKGROUND

The application of structural integrity and fitness-for-service (FFS) assessment procedures (1-4) of ageing structures is increasing in the fossil fuel power, oil and gas production, refining and petrochemical industries. An essential input for these procedures is material properties data. Conservative data for virgin parent materials are available in design codes and standards. However, FFS assessments are most often undertaken on aged welded components for which mechanical properties data may not be available.

Instrumented indentation testing (IIT[+]), provides a means of estimating materials properties (tensile properties, fracture toughness and surface residual stress), without destructive removal of samples from business- and safety-critical plant and equipment (5). IIT was developed from the conventional hardness test, but is distinctly different. An indentor is driven at an approximately constant rate (0.3-6mm/min) into the surface of the material to be measured, and the load required to reach the penetration depth is recorded. At certain depths the indentor is unloaded and withdrawn slightly and then reloaded to a greater depth in a series of increments until the test is complete. An indentation load versus depth curve is obtained from this measurement procedure. The technique relies on plastically deforming the material.

The current project will undertake comparative tests between (IIT) and destructive (small-scale) tests, on parent material and weldments with and without PWHT. The following will be measured and compared: (a) surface residual stress, (b) tensile properties; and (c) fracture toughness. Similar comparative post-exposure tests on aged material extracted from retired plant and equipment, as supplied by individual sponsors to the project, will also be carried out. Measured material properties data and lower bound published data will be used with established defect assessment procedures to examine the potential benefits of IIT technology.

[+] Also known as ABI (automated ball indentation); AIT (automated indentation testing); MIT (macro-indentation technique); etc.

OBJECTIVES

To examine the reliability of IIT on ferritic steel (e.g. C-Mn, Cr-Mo, etc), austenitic steel, aluminium alloy, and titanium alloy, under realistic field conditions for measurement of tensile properties, fracture toughness and surface residual stress, for use in structural integrity and defect assessments of ageing plant and equipment.

BENEFITS

Plant owners and plant assessment engineers will benefit from an independent evaluation of IIT. Practical recommendations on the use of IIT in structural integrity assessment will be provided to enable engineers to assess ageing welded plant.

More accurate and less conservative assessments will be achieved while avoiding removal of material for mechanical tesing.

APPROACH

1. Review the technical basis and the algorithms in IIT.

2. Review the current ASTM and ISO standard developments for IIT.

3. Undertake comparative non-destructive (IIT) and destructive (small-scale) tests, on parent material and weldments (with and without PWHT), including measurements of (a) surface residual stress, (b) tensile properties; and (c) fracture toughness.

4. Undertake similar comparative post-exposure tests on aged material extracted from retired plant and equipment, as supplied by individual Sponsors to the Project.

5. Perform a comparative defect assessment with both types of material properties data, and lower bound published data, to appraise the benefits of IIT technology.

The project will be undertaken with input from FRONTICS (South Korea) a supplier of IIT equipment.

REPORTING

Progress reports providing details of experimental procedures and test data will be issued every six months, prior to Sponsor Group meetings. At the close of the projects, a Final Report detailing the work performed and the main results will be presented.

PRICE AND DURATION

The indicative budget for this proposed project is £144,000 and eight Sponsors are sought, paying approximately £18,000 each. The duration of the Project is 12 months.

DELIVERABLES

- Independent assessment of the accuracy of IIT by comparison with conventional destructive test methods.

- Recommendations on the correct use of IIT as well as the use of IIT results in fitness for service assessments.

- A code of practice on non-destructive fitness for service assessment.

LAUNCH MEETING

A Launch meeting will be held:
Date: 12 July 2006,
Time: 11.00 UK Time
Venue: TWI Ltd, Granta Park, Great Abington, Cambridge, CB1 6AL, UK.

For further information please contact:

Dr Afrshin Motarjemi
(afshin.motarjemi@twi.co.uk)

REFERENCES

1. API RP 579: 'Recommended practice on fitness for service assessment', 1st Edition, American Petroleum Institute, 2000.

2. BS 7910:2005: 'Guide to methods for assessing the acceptability of flaws in metallic structures'. British Standards Institution, London, UK, 2005.

3. R5: 'Assessment procedure for the high temperature response of structures', Issue 3, British Energy.

4. R6: 'Assessment of the integrity of structures containing defects', Revision 4, Amendment 2, British Energy.

5. Motarjemi A and Speck J: 'Trials using the Instrumented Indentation Tehnique (IIT)', Inspectioneering Journal, March 2006. http://www.twi.co.uk/j32k/protected/band_8/spjsmar05.html

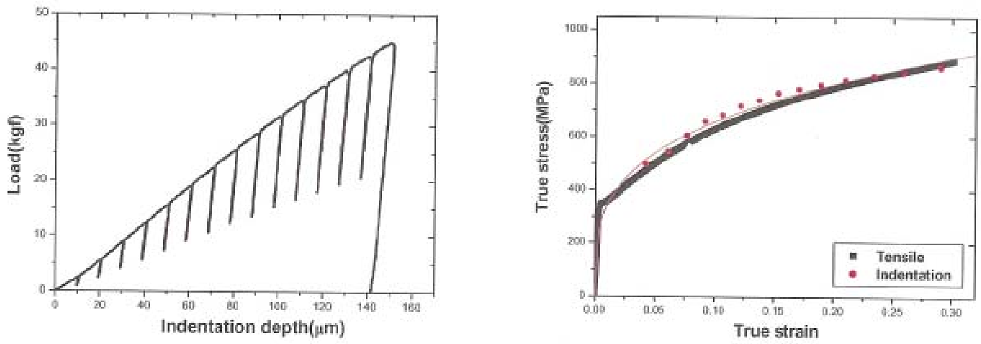
APPENDIX A: UNDERLYING THEORY

DETERMINATION OF TENSILE PROPERTIES

An indentation load depth curve is obtained from an indentation test. A true stress-true strain curve can then be derived from the load-depth curve given knowledge of the broad type of material, by considering the indentation stress fields and deformation shape and depth.

Stress and strain values equivalent to those from a uniaxial tensile test can be defined (Fig A1) in terms of the measured indentation contact parameters, such as contact depth, indenter shape and the morphology of the deformed sample surface.

When a set of equivalent uniaxial stress-strain data has been obtained from a number of indentations, the user can then choose an appropriate curve to fit through the data (Fig A1).



(a) (b)

Fig A1 Load-indentation depth curve (a) and true stress-strain curve derived (b) using IIT algorithm (Courtesy FRONTICS).

The intercept of the elastic loading line (assumed to be straight and to have a slope equal to the slope of the measured unloading curves) with the fitted curve gives an estimated value of the 0.2% yield strength. The slopes of the unloading curves are taken as Elastic Modulus. The predicted value of the ultimate tensile strength is defined as the point at which uniform elongation (ε_u) is equal to the work hardening exponent (n).

DETERMINATION OF SURFACE RESIDUAL STRESS

Indentation load-depth curves are shifted with the magnitude and direction of the residual stress. Nevertheless, contact depths in the stress-free and stressed states are constant at a specific indentation load. This means that residual stress induces additional load to keep contact depth constant at the same load. By taking these phenomena into account, surface residual stress can be obtained directly from the indentation load-depth curve, as shown in the Fig A2, by knowing the curve of a stress free specimen.

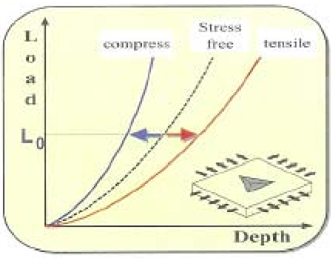


Fig A2 The effect of compressive and tensile residual stresses on the position of the load-indentation depth curve (Courtesy FRONTICS).

DETERMINATION OF FRACTURE TOUGHNESS

Critical fracture toughness in terms of K_{JC} (obtained from J_{IC}) can be expressed as a function of Elastics modulus and surface energy required to create a crack. The latter can be worked out by integration of the area under a load-indentation depth curve up to an indentation depth (h*) at which, due to the high internal pressure, voids or local damages are found.

By locally damaging the material underneath an indenter, due to the high indentation pressure, material's Elastic Modulus will be reduced to an effective or reduced value (E_{eff} or E_r) corresponding to h*, as shown in Fig A3. This effective modulus and critical indentation depth of h* are the main parameters should be used to evaluate a critical value of fracture toughness.

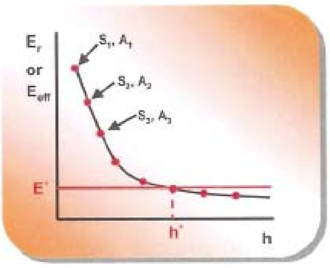


Fig A3 Reduction in Elastic Modulus as a result of local damage (formation of voids) underneath the indenter at. h* is the depth at which voids are formed (Courtesy FRONTICS).

4. Patents

(1) Published International Patents

	Appl. #	Patent #	Title
US	10/209,237	US 6,718,820 B2	An apparatus for Indentation Test and Method for Measuring Mechanical Properties Using it.
US	10/404,816	US 6,851,300 B2	Apparatus for measuring residual stress, methods of measuring residual stress and residual stress data using the apparatus, and recoding medium for storing software of the residual stress measuring methods
		US 7,472,603 B2	Evaluating Method of the residual Stress Determining method using the continuous indentation method
US	11/667,229	7487051	EAVLUATING METHOD OF THE FRACTURE TOUGHNESS USING THECONTINUOUS INDENTATION
Japan	2001-228789	3702203	連続圧入試験のための圧入試験機、これを用いた物性測定方法及び物性計算方法
Japan	2003-100724	3959484	残留応力測定装置、これを用いた残留応力データ測定方法並びに残留応力測定方法,及びこの残留応力測定プログラムを記録したコンピュータ読み取り可能な記録媒体
EU	1836473		Evaluating Method of the Residual Stress Determining Method Using the continuous Indentation Method

(2) PCT

	Appl. #	Title
PCT	PCT/KR2007/000621	ESTIMATION OF NON-EQUIBIAXIAL STRESS USING INSTRUMENTED INDENTATION TECHNIQUE
	PCT/KR2005/003947	Evaluating Method of the Residual Stress Determining Method Using the continuous Indentation Method
	PCT/KR2005/003039	EAVLUATING METHOD OF THE FRACTURE TOUGHNESS USING THECONTINUOUS INDENTATION

(3) Korean Patent cases

Tensile Properties	Residual Stress	Fracture toughness	Etc.
5	2	1	4

Measurement of Tensile Properties

- US 6,718, 820 B2: "An apparatus for indentation test and method for measuring mechanical properties using it."

US006718820B2

(12) **United States Patent**
Kwon et al.

(10) **Patent No.:** **US 6,718,820 B2**
(45) **Date of Patent:** **Apr. 13, 2004**

(54) **APPARATUS FOR INDENTATION TEST AND METHOD FOR MEASURING MECHANICAL PROPERTIES USING IT**

(75) Inventors: **Dong-il Kwon**, Kangnam APT. #6-306, Bangbae 3-dong, Seocho-gu, Seoul (KR); **Yeol Choi**, Seoul (KR); **Yun-hee Lee**, Kyeongsangbuk-do (KR)

(73) Assignees: **Frontics, Inc.** (KR); **Dong-il Kwon** (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/209,237**

(22) Filed: **Jul. 31, 2002**

(65) **Prior Publication Data**

US 2004/0020276 A1 Feb. 5, 2004

(51) **Int. Cl.**[7] **G01N 3/48**

(52) **U.S. Cl.** **73/81**; 73/82; 73/83; 73/85; 73/87

(58) **Field of Search** 73/81, 82, 83, 73/84, 85, 86, 87

(56) **References Cited**

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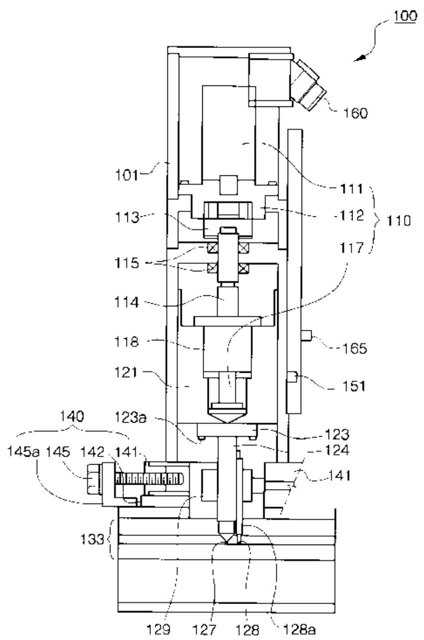
Primary Examiner—Hezron Williams
Assistant Examiner—David Rogers
(74) *Attorney, Agent, or Firm*—Hayes Soloway P.C.

(57) **ABSTRACT**

The present invention relates to an apparatus for indentation test, for measuring mechanical properties in the field. The present invention provides an apparatus which is suitable for measuring mechanical properties without compensative experimental constant for the analysis of measured data. The present invention provides an apparatus which is safe for testing the materials by utilizing a sensor for controlling indenter movement.

8 Claims, 13 Drawing Sheets



Measurement of Fracture Toughness

- US 7,487,051 B2 : - “Evaluating Method of The Fracture Toughness Using The Continuous Indentation Method.”

US007487051B2

(12) **United States Patent**
Kim et al.

(10) **Patent No.:** **US 7,487,051 B2**
(45) **Date of Patent:** **Feb. 3, 2009**

(54) **EVALUATING METHOD OF THE FRACTURE TOUGHNESS USING THE CONTINUOUS INDENTATION METHOD**

(75) Inventors: **Kwang-Ho Kim**, Seoul (KR); **Jung-Suk Lee**, Gyeonggi-do (KR); **Yang-Won Seo**, Seoul (KR); **Yeol Choi**, Seoul (KR)

(73) Assignee: **Frontics, Inc.** (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/667,229**

(22) PCT Filed: **Sep. 14, 2005**

(86) PCT No.: **PCT/KR2005/003039**

§ 371 (c)(1), (2), (4) Date: **May 8, 2007**

(87) PCT Pub. No.: **WO2006/052060**

PCT Pub. Date: **May 18, 2006**

(65) **Prior Publication Data**

US 2008/0010031 A1 Jan. 10, 2008

(30) **Foreign Application Priority Data**

Nov. 9, 2004 (KR) 10-2004-0091013

(51) **Int. Cl.**
G01L 1/00 (2006.01)

(52) **U.S. Cl.** **702/42**; 73/81; 73/82; 73/865.3; 702/33

(58) **Field of Classification Search** 702/33-35, 702/42, 44, 156; 73/81, 82, 856, 865.3; 324/209, 324/223
See application file for complete search history.

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2003/0183021 A1	*	10/2003	Holmberg	73/865.3

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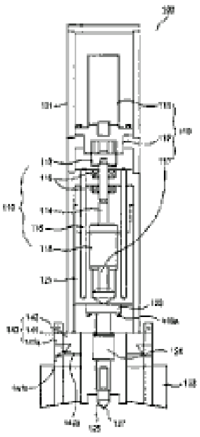
* cited by examiner

Primary Examiner—John H Le
(74) *Attorney, Agent, or Firm*—Harness, Dickey & Pierce, P.L.C.

(57) **ABSTRACT**

The present invention relates to a method of evaluating the fracture toughness of a material using the continuous indentation technique. In the method of this invention, the stress coefficient, strain hardening modulus and yield stress of the material are determined using the continuous indentation technique and, thereafter, the reduced elastic modulus (Er) of the material is calculated. The effective elastic modulus and the initial elastic modulus are calculated and, thereafter, the damage parameter is calculated using the void volume fraction. The critical elastic modulus and the characteristic fracture initiation point of the indentation depth are determined using the damage parameter and, thereafter, the fracture toughness of the material is evaluated. The present invention is advantageous in that the fracture toughness of a brittle material can be evaluated precisely using a nondestructive evaluation technique.

10 Claims, 4 Drawing Sheets



Measurement of Residual Stress

- US 6,851,300 : - "Apparatus for determining residual stress, method for determining residual stress data using it, residual stress determining method using it and recoding medium thereof."

US006851300B2

(12) **United States Patent**
Kwon et al.

(10) **Patent No.: US 6,851,300 B2**
(45) **Date of Patent: Feb. 8, 2005**

(54) **APPARATUS FOR DETERMINING RESIDUAL STRESS, METHOD FOR DETERMINING RESIDUAL STRESS DATA USING IT, RESIDUAL STRESS DETERMINING METHOD USING IT AND RECORDING MEDIUM THEREOF**

(75) Inventors: **Dongil Kwon**, Seoul (KR); **Yunhee Lee**, Kyungsangbuk-do (KR); **Dongil Son**, Seoul (KR)

(73) Assignee: **Frontics Inc.** (KR)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 28 days.

(21) Appl. No.: **10/404,816**

(22) Filed: **Apr. 1, 2003**

(65) **Prior Publication Data**

US 2003/0217591 A1 Nov. 27, 2003

(30) **Foreign Application Priority Data**

Apr. 4, 2002 (KR) 10-2002-0018521

(51) **Int. Cl.**[7] **G01N 3/00**
(52) **U.S. Cl.** **73/85**
(58) **Field of Search** 73/81, 85, 78, 73/83

(56) **References Cited**

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S. Suresh et al., "A new method for estimating residual stresses by instrumented sharp indentation", Acta mater., vol. 46, No. 16, 1998, pp. 5755–5767.

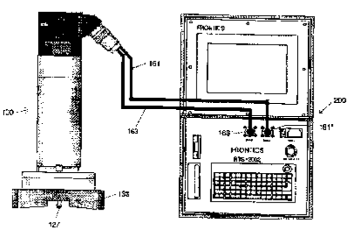
(List continued on next page.)

Primary Examiner—Max Noori
(74) *Attorney, Agent, or Firm*—Harness, Dickey & Pierce, P.L.C.

(57) **ABSTRACT**

Disclosed herein is an apparatus for measuring residual stress, methods of measuring residual stress data and residual stress using the apparatus, and a recording medium for storing software of the residual stress measuring method. The present invention is advantageous for evaluation of a mechanical material property and is non-destructive. Further, the present invention is widely applied to fields ranging from a microscopic area, such as a thin film or micro device, to a large-sized structure, and is not influenced by a microstructure by controlling the range of an applied load. Further, the measuring apparatus of the present invention is minimized in its volume to be easily attached to an actual structure. Further, in the present invention, various attaching devices are employed, thus enabling the apparatus to be attached to various materials regardless of the size and type of object materials to measure residual stress. Further, the measuring apparatus of the present invention is horizontally movable, so there is no need to move an apparatus body itself so as to take measurements at several positions of several materials. Further, the present invention does not require separate measurements for correcting experimental constants at the time of analyzing measured data.

18 Claims, 14 Drawing Sheets



 # Measurement of Residual Stress

- US 2008/0141782 A1// US 7,472,603 B2: - "Evaluating Method of The Residual Stress Determining Method Using The Continuous Indentation Method."

US 20080141782A1

(19) **United States**
(12) **Patent Application Publication**
Kim

(10) **Pub. No.: US 2008/0141782 A1**
(43) **Pub. Date: Jun. 19, 2008**

(54) **EVALUATING METHOD OF THE RESIDUAL STRESS DETERMINING METHOD USING THE CONTINUOUS INDENTATION METHOD**

(75) Inventor: **Kwang Ho Kim**, Seoul (KR)

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(73) Assignees: **Frontics, Inc.**, Seoul (KR); **Won Seok Jung**, Masan (KR)

(21) Appl. No.: **11/793,274**

(22) PCT Filed: **Nov. 22, 2005**

(86) PCT No.: **PCT/KR05/03947**

§ 371 (c)(1), (2), (4) Date: **Jun. 15, 2007**

(30) **Foreign Application Priority Data**

Dec. 16, 2004 (KR) 10-2004-0106759

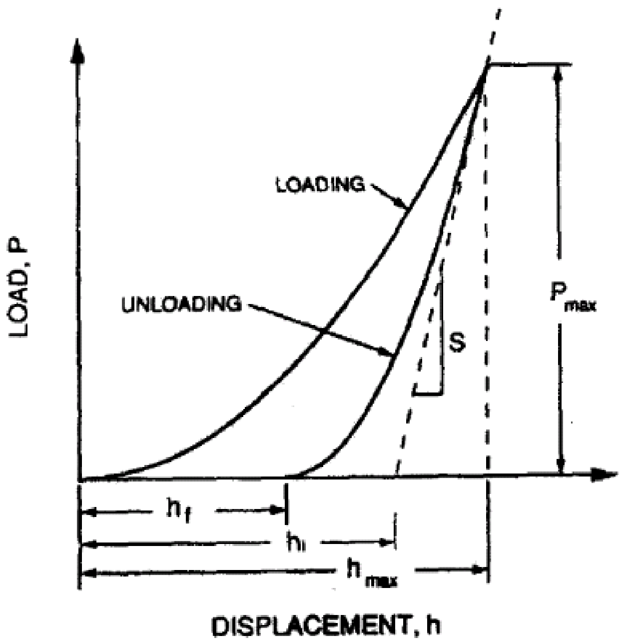
Publication Classification

(51) **Int. Cl.**
G01N 11/00 (2006.01)

(52) **U.S. Cl.** **73/823**

(57) **ABSTRACT**

The present invention relates to a method of measuring residual stress and, more particularly, to a residual stress measuring method using a continuous indentation tester. Due to pile-up and sink-in of a material or a blunted tip, a conventional residual stress measuring method cannot compensate for error of a real contact (indentation) depth or directly remove stress through a thermal or mechanical technique in the conventional method of measuring residual stress of a weldment, so that it is very difficult to estimate a stress-free reference curve or to quantitatively measure residual stress. However, the present invention can precisely estimate a stress-free curve of a weldment using an indentation strength ratio (OIT ratio) of a stress-free base metal to the weldment, and compensates for error, occurring in the measurement of a material having a weldment or an anisotropic stress structure, based on the indentation strength ratio, thereby more precisely measuring residual stress. Thus, unlike the conventional method, the present method can minimize error occurring in the residual stress measuring process, and agrees with actual models.



Application case

FRONTICS has various applications of oil refinery and power plant facilities over a decade. Key examples per subjected materials and services list for oil refinery and power plant equipment for over a decade are as follows.

1. Application

Power Plants

Turbine rotor	Boryeong Thermal Power Plant in Korea
Turbine casing, IP Rotor, ICV	Ulsan power plant in Korea
TBN/Thrust bearing shaft	Korea East·West Power Cooperation, Sanchun-Yangsu
Forged shaft	Poscoss in Korea
Turbine case	Boryeong power plant in Korea
HP Rotor	Boryeong power plant in Korea
Boiler tube	Dangjin power plant 7&8 # in Korea
Materials of Power plant	EDF – Electricite De France

Nuclear Power Plant

Materials of nuclear power plant	Wolsong nuclear power plant in Korea
Cooling water line	Kori nuclear power plant in Korea
Steam generator	Doosan Heavy Industries & Construction

Oil Refinery Facilities

Heater tube	Hyundai Oil in Korea
Freeze tube	Casper, WY, US (in Shell)
Reactor	S-Oil in Korea
Weld Overlay	SK Energy in Korea

Natural Gas Pipeline

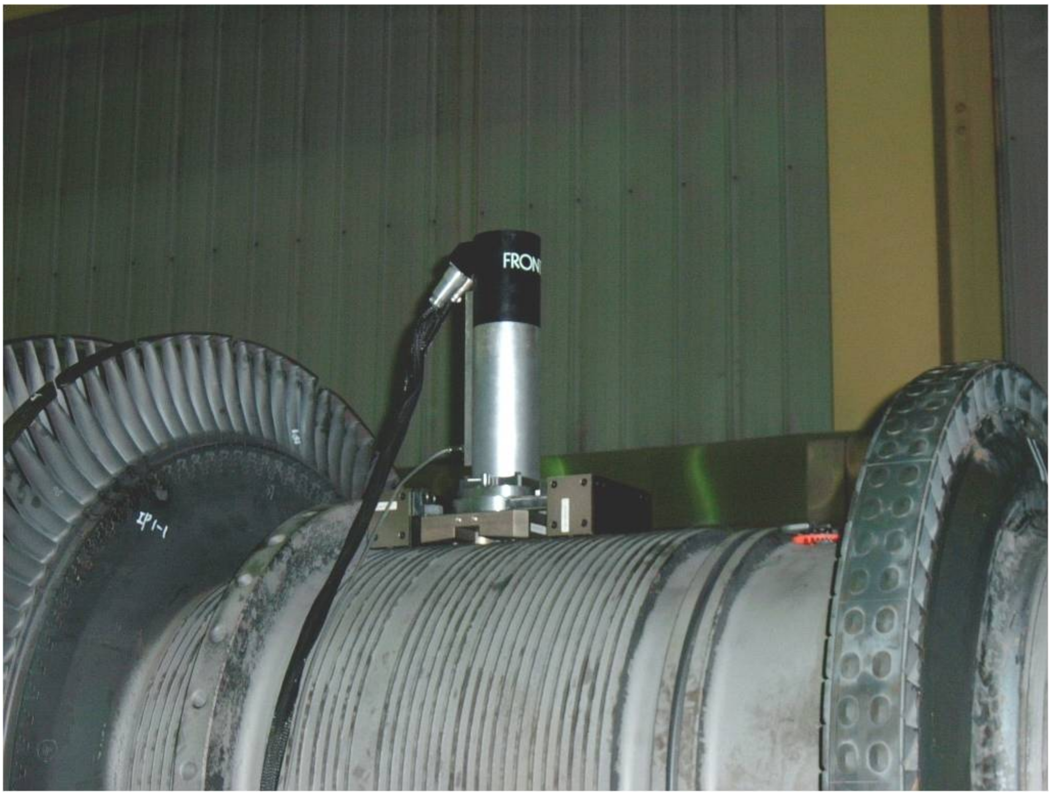
Weldment of API X65	Alcoa in US
API pipe	GE Power System
API pipe	Chevron Texaco

2. Application list of Power plant & Oil refinery facilities

2001 – 3 cases
2002 – 6 cases
2003 – 8 cases
2004 – 10 cases
2005 – 12 cases
2006 – 5 cases
2007 – 7 cases
2008 – 10 cases
2009 – 15 cases
2010 – 1 cases

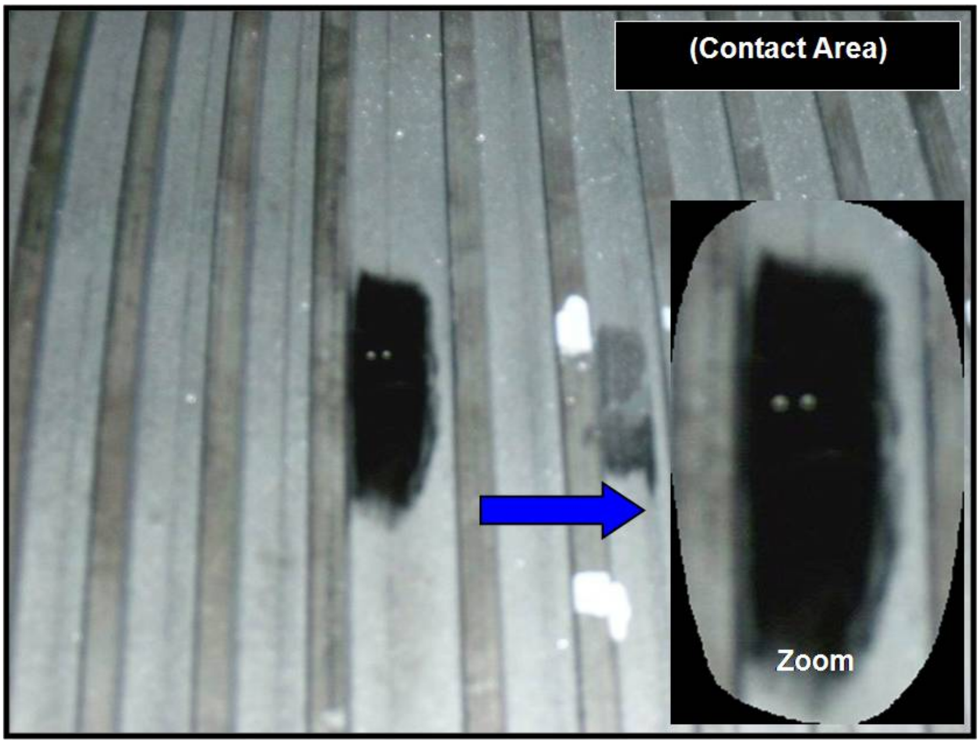
Power plant – Turbine rotor

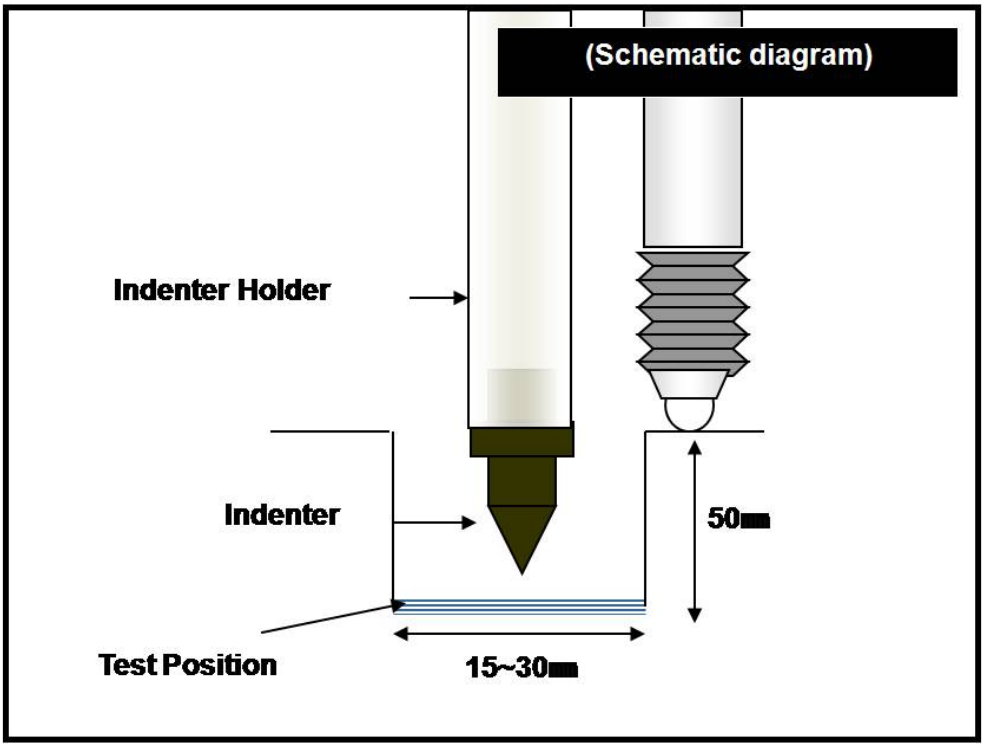
- **Place**: Boryeong Thermal Power Plant in Korea (April, 2002)
- **Object**: Turbine Rotor
- **Condition**: Dia. 36~60 inch (Rotor of operated during 22 years)
- **Material**: ASTM A470 C1.8
- **Attachment**: Curvature magnet system
- **Remark**: Safety evaluation of facilities during rotor repair



The test subject was a turbine rotor used for 22 years, and the test was conducted by applying curvature magnet system, as the shape was circular. Unusual point was that the test spot located in a narrow region 15 – 30 mm inside uneven section.

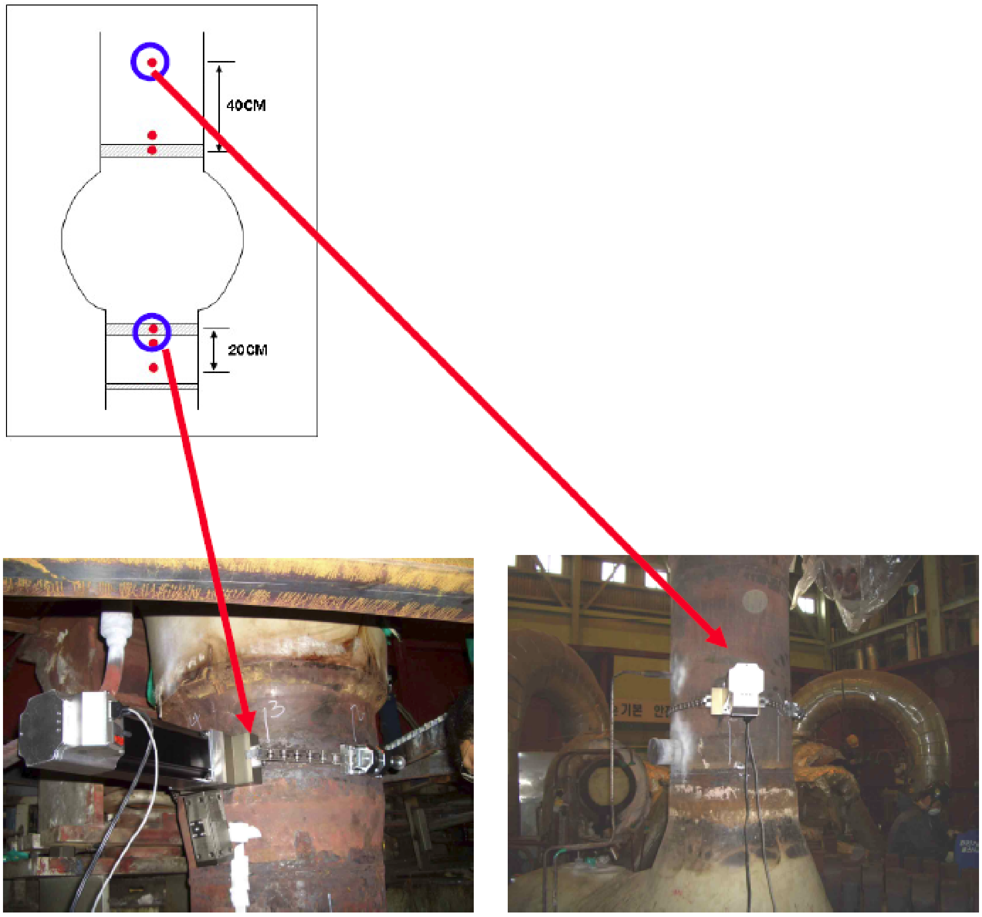
Boryeong Thermal Power Plant in Korea (April, 2002)





Power plant – Turbine casing, IP Rotor, ICV

- **Place**: Ulsan power plant in Korea (2005.05)
- **Object**: Determination of replacement and repair for power plant facilities
- **Condition**: Tensile strength evaluation
- **Material**: Turbine casing, IP Rotor, ICV
- **Attachment**: Chain system, Plate-magnet system
- **Remark**: Measurement of strength deviation for power plants pipeline damaged by high-temperature



The test subjects were ICV, IP Rotor and Turbine casing of a thermal power plant. We have tested them applying lightweight chain system and flat magnet system, as sizes of the test regions were different.

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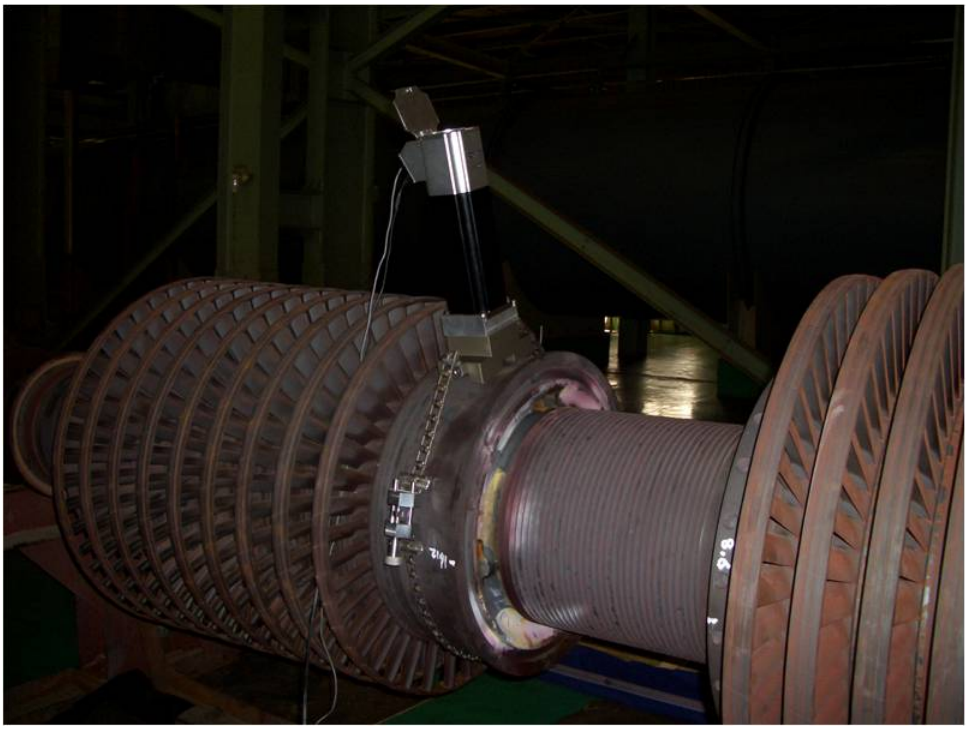
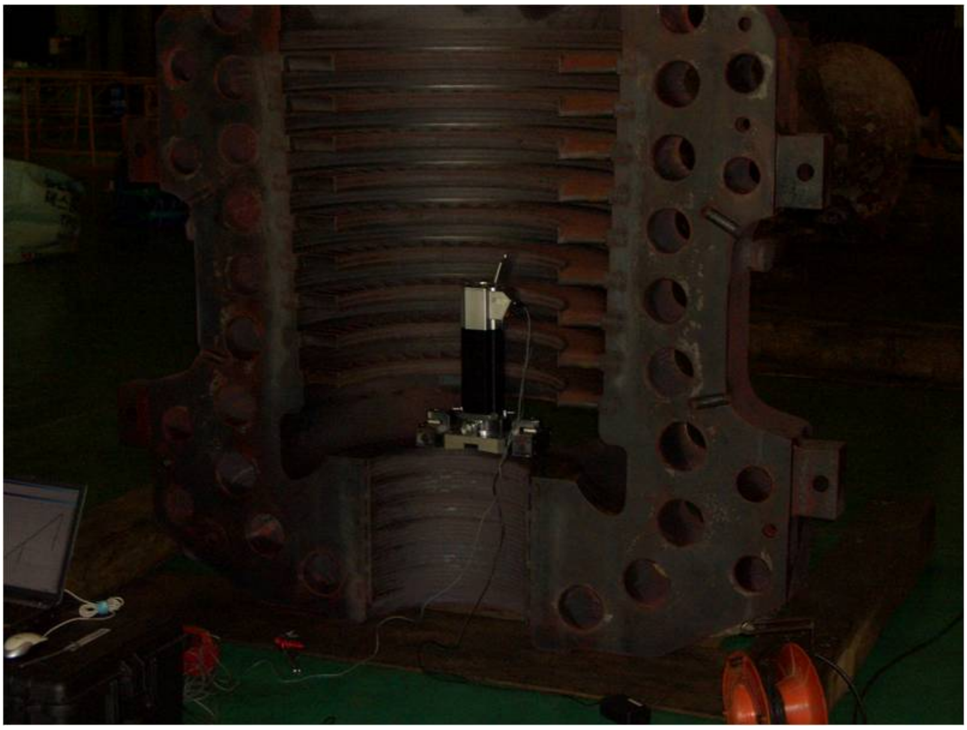
Ulsan power plant in Korea (2005.05)

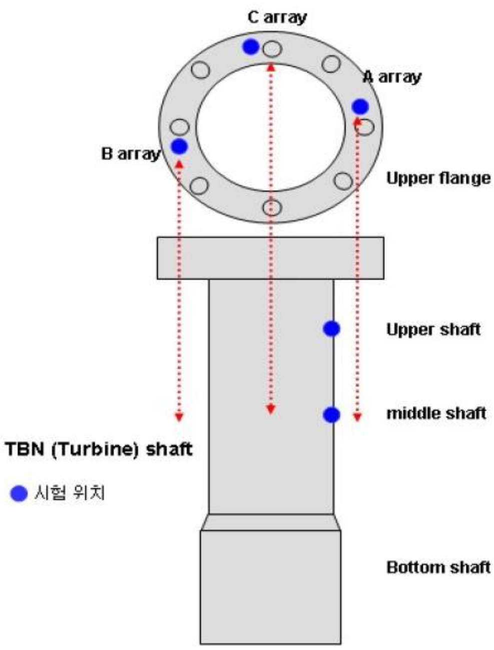
Ulsan power plant in Korea (2005.05)





Power plant – TBN/Thrust bearing shaft

- **Place**: Korea East·West Power Cooperation, Sanchun-Yangsu (September, 2005)
- **Object**: TBN/Thrust bearing shaft
- **Condition**: Tensile properties of TBN/thrust bearing shaft (upper, middle, bottom)
- **Attachment**: Curvature & flat magnetic system
- **Remark**: Integrity assessment of bearing shaft



The test subjects were turbine shaft and turbine bearing shaft of a power plant. Test location was the side of shaft and the top connected to other component. The test was conducted on the side of shaft by applying curvature magnet system and on the top by flat magnet system.

Korea East·West Power Cooperation, Sanchun-Yangsu (September, 2005)

Power plant – Forged shaft

- **Place**: Poscoss in Korea (August, 2008)
- **Object**: Forged shaft
- **Attachment**: Curvature magnetic system
- **Remark**: Stress generation by rough grinding during processing

The test subject was forged shaft that was tested by applying curvature magnet system. Purpose of the test was to evaluate change of properties per each processing stage and change of residual stress.

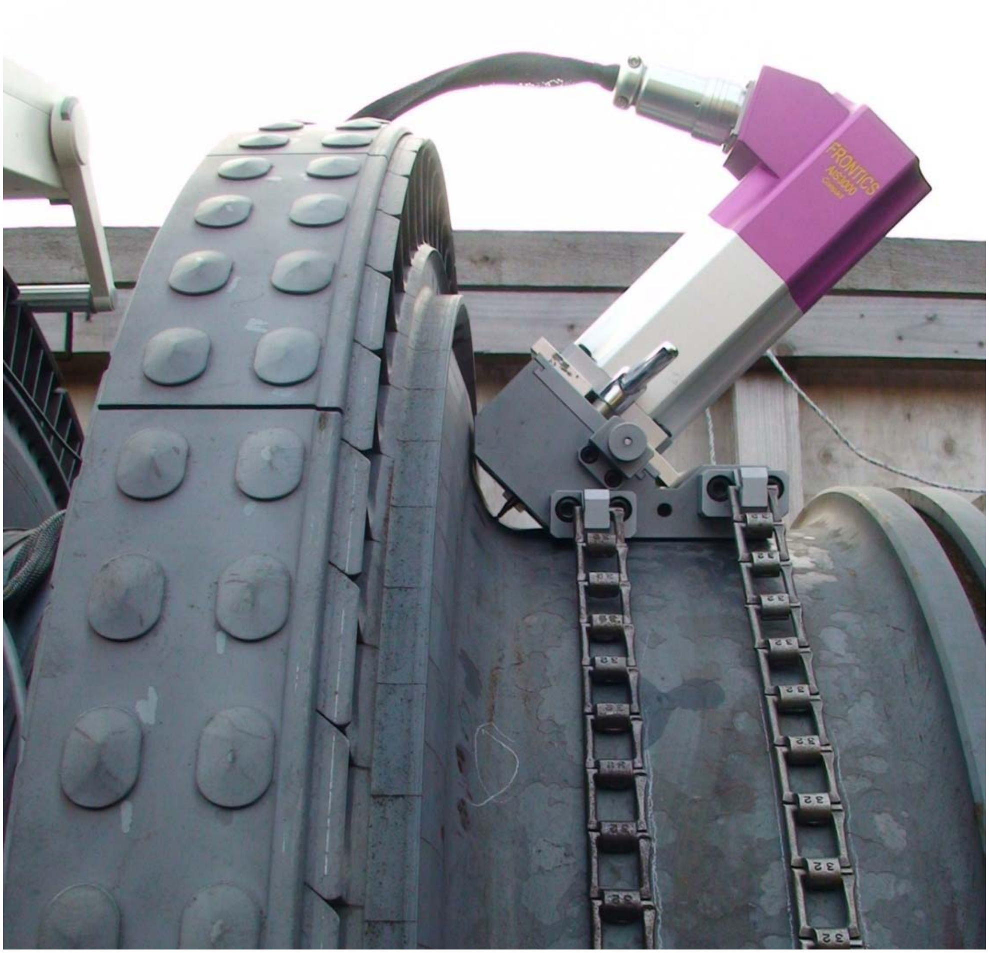
Power plant – Turbine case

- **Place**: Boryeong power plant in Korea (August, 2009)
- **Object**: Turbine case
- **Attachment**: Flat magnet system

The test subject was turbine rotor case, and flat magnet system was applied, considering the shape. Purpose of the test was the evaluation of abrasion degree and life span, and the required properties evaluation was carried out.

Power plant – HP Rotor

- **Place**: Boryeong power plant in Korea (August, 2009)
- **Object**: HP Rotor groove
- **Attachment**: Special attachment system



The test subject was HP rotor, and the location of the test was groove section. We made the special attachment system that was applied to the test, considering the shape. Purpose of the test was to estimate finally the lifetime by evaluating the physical properties of the subjected section.

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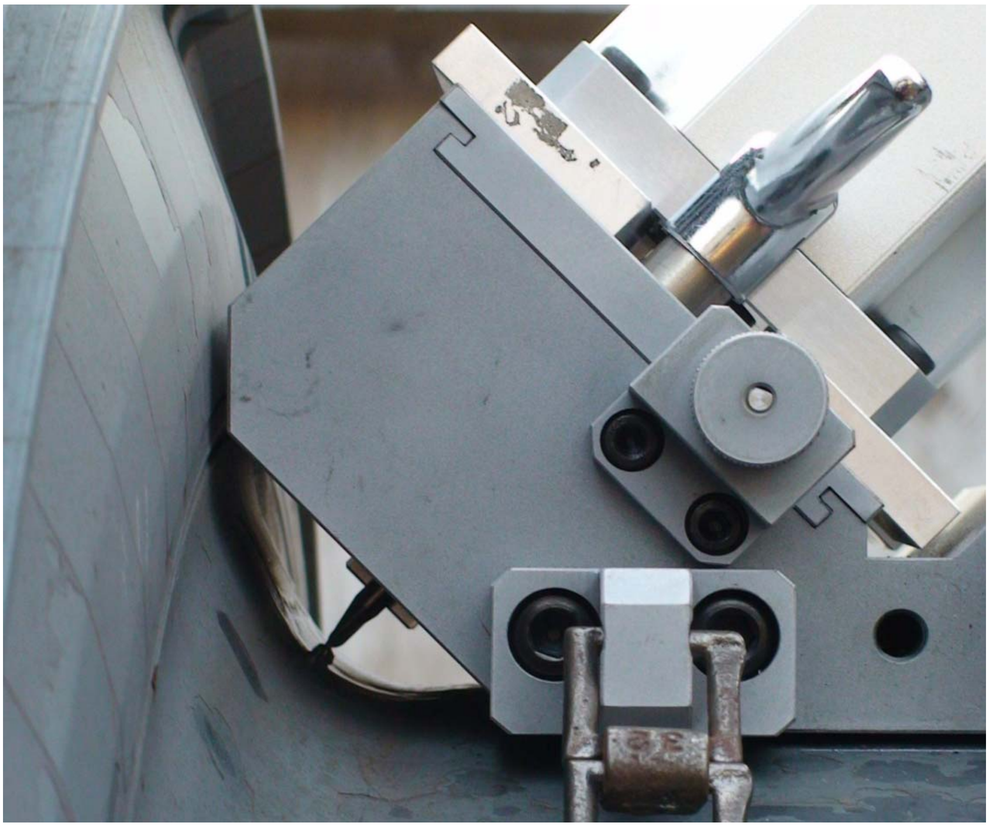
Gasan-dong, Geumcheon-gu, Seoul, Korea

Boryeong power plant in Korea (August, 2009)



Power plant – Boiler tube

- **Place**: Dangjin power plant 7&8 # in Korea (August, 2008)
- **Object**: boiler tube
- **Condition**: ASME SA213T23 (Bainite + Martensite)
- **Attachment**: V-block system
- **Remark**: 800MW Boiler tube (failure incident in-service)

The test subject was T23 boiler tube applied to a power plant, and the attachment of V-block system was applied. Test purpose was to evaluate properties and residual stress of weldment before and after heat treatment. The actual evaluation result confirmed that the residual stress was stabilized and tensile properties were maintained by the conditions of heat treatment..

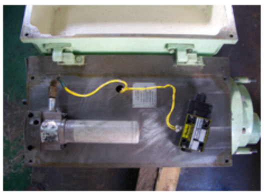
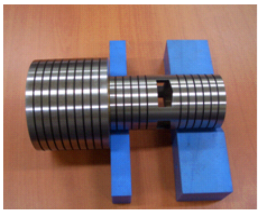
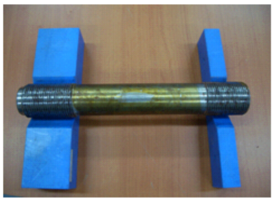
Power plant – Materials of Power plant

- **Place**: EDF – Electricite De France (April, 2005)
- **Material**: Material of Power plant
- **Attachment**: MPS system
- **Remark**: Blind test

This test was conducted to evaluate the properties of the electricity generation-related component material from Electricite De France (EDF). There was not any information of the material, and the test was conducted with specimens.

Nuclear Power plant – Materials of nuclear power plant

- **Place**: Wolsong nuclear power plant in Korea (March, 2007)
- **Object**: Materials of nuclear power plant
- **Remark**: Check materials and selection replacement materials

			
Valve Disk	Valve Plunger	Valve casing	Piston
			
HP turbine housing	Power Piston	Turbine bolt	Turbine valve Operating sleeve

The subjects were components widely used at nuclear power plant facility. The user had been spending lots of money, since the components had been supplied by the manufacturer without information concerning the materials. Purpose of the service was to check them by indentation test and properties analysis in order to replace them to domestic components. We have provided information of the final alternative materials after checking materials selection and the method of heat treatment on 8 target subjects.

Wolsong nuclear power plant in Korea (March, 2007)

 # Selection Materials

<table>
<tr><th colspan="2">Specimen</th><th>Selection Materials</th><th>Remark</th></tr>
<tr><td rowspan="2">Valve disk</td><td>Base metal</td><td>ASTM A27</td><td></td></tr>
<tr><td>Coating</td><td>ASTM F75</td><td>STELLITE® 21 medical grade</td></tr>
<tr><td colspan="2">Vavle Plunger</td><td>ASTM A36</td><td></td></tr>
<tr><td colspan="2">Valve casing</td><td>ASTM A27</td><td></td></tr>
<tr><td colspan="2">Piston</td><td>ASTM A322 Gr.4130 (AISI 4130)</td><td></td></tr>
<tr><td colspan="2">HP turbine housing</td><td>ASTM A356 Gr.10 (2.25Cr-1Mo Steel)</td><td></td></tr>
<tr><td rowspan="2">Power piston</td><td>Base metal</td><td>ASTM A322 Gr.1330 (AISI 1330)</td><td></td></tr>
<tr><td>Contact region</td><td>MICr3 (KS D0212-95)</td><td></td></tr>
<tr><td colspan="2">Turbine bolt</td><td>ASTM A470 Grade D (1Cr-Mo-V steel)</td><td></td></tr>
<tr><td rowspan="2">Turbine valve operating sleeve</td><td>Base metal</td><td>ASTM A182 F11 (1.25Cr-0.5Mo steel)</td><td></td></tr>
<tr><td>Coating</td><td>ASTM F75</td><td>STELLITE® 21 medical grade (coating)</td></tr>
</table>

Wolsong nuclear power plant in Korea (March, 2007)

Results of IIT

Specimen		Unit	True Value		Engineering Value	
			YS	UTS	YS	UTS
Valve disk	Base metal	MPa	409.5	605.5	407.4	535.7
		kg/mm^2	41.7	61.7	41.5	54.6
	Coating	MPa	558.7	690.3	554.5	632.9
		kg/mm^2	57.0	70.4	56.6	64.6
Valve Plunger		MPa	913.6	1251.7	906.8	1115.3
		kg/mm^2	93.1	127.6	92.4	113.7
Valve casing		MPa	463.1	623.6	460.4	562.8
		kg/mm^2	47.2	63.6	46.9	57.4
Piston		MPa	927.2	1104.1	909.5	1072.6
		kg/mm^2	94.6	112.7	92.8	109.5
HP turbine housing		MPa	487.8	612.8	485.5	565.2
		kg/mm^2	49.7	62.5	49.5	57.6
Power piston		MPa	223.5	473.4	222.7	391.2
		kg/mm^2	22.8	48.3	22.7	39.9
Turbine bolt		MPa	732.2	1013.2	727.8	906.8
		kg/mm^2	74.6	103.3	74.2	92.4
Turbine valve operating sleeve	Base metal	MPa	1627.2	1872.8	1583.7	1774.9
		kg/mm^2	166.0	191.1	161.6	181.1
	Coating	MPa	558.7	690.3	554.5	632.9
		kg/mm^2	57.0	70.4	56.6	64.6

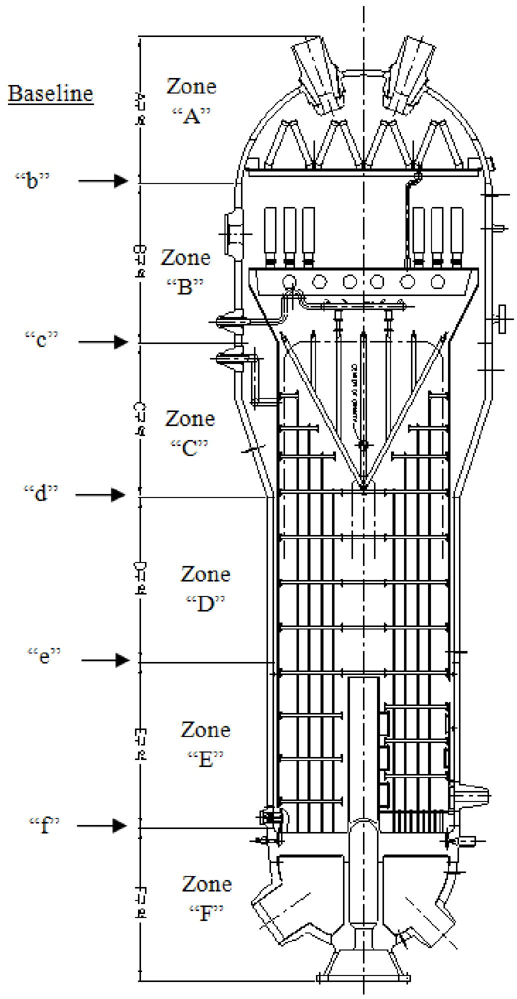
Nuclear Power plant – Cooling water line

- **Place**: Kori nuclear power plant (January, 2002)
- **Object**: Kori No.1 main cooling water line of nuclear power plant (Dia:12 in)
- **Condition**: Operating Temperature: 60℃,/90° pipe of elbow type
- **Material**: ASTM A106 B (base metal), AWS E7016(weld metal)
- **Attachment**: Chain system
- **Remark**: Mechanical Properties of base material, weldment and HAZ for main cooling water line of nuclear plant aged more than 20 years

The test subject was cooling water line of a nuclear power plant, and chain system was applied, considering the shape. Test location was the weldment of elbow and pipe, and we have evaluated the properties change during last 20 year use.

Nuclear Power plant – Steam generator

- **Place**: Doosan Heavy Industries & Construction (December, 2008)
- **Object**: Steam generator of nuclear power plants
- **Attachment**: Curvature magnet system & Special attachment system
- **Remark**: Evaluation of residual stress

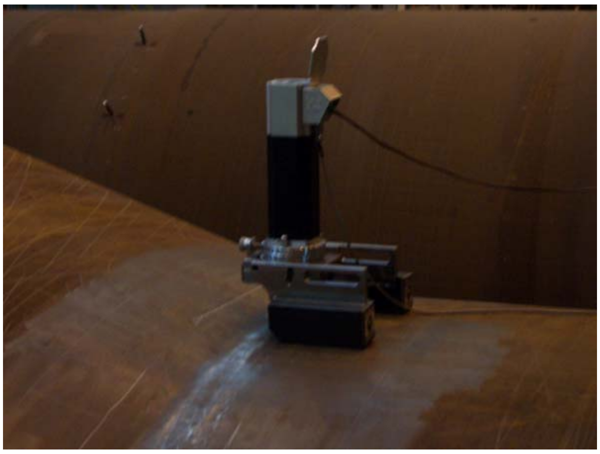


The test subject was the steam generator of a nuclear power plant. Considering the shape, curvature magnet system and special attachment system were applied. Purpose of the test was the stress evaluation on the location where external impact had been applied.

Doosan Heavy Industries & Construction (December, 2008)

Curvature magnet system - Dovetail Slider

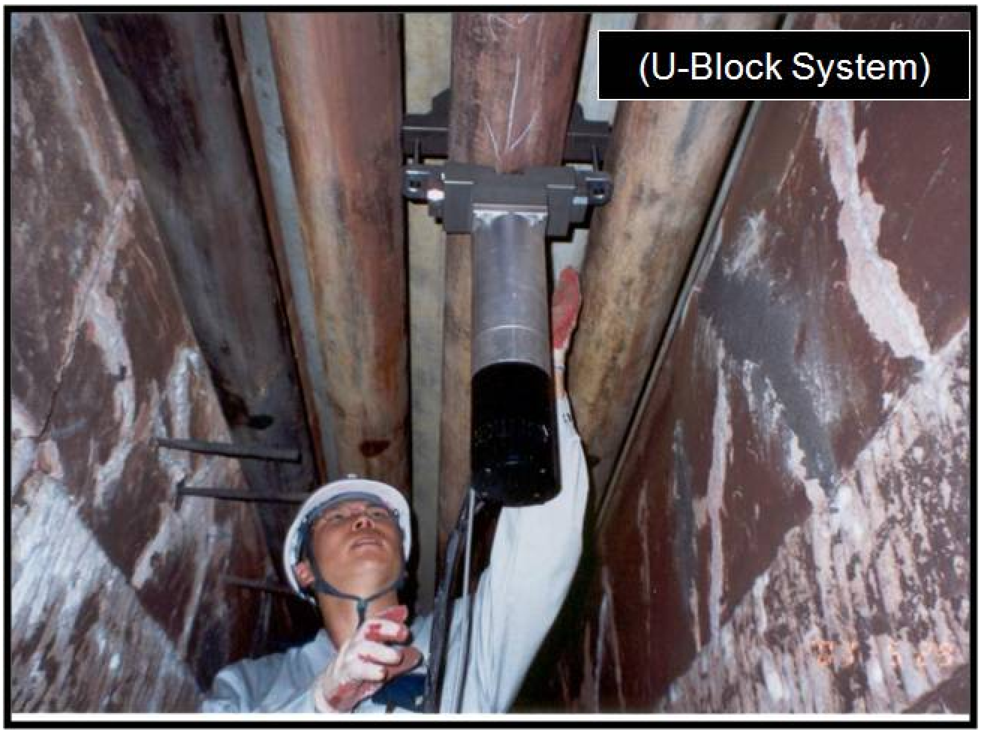
Curvature magnet system - Long Dovetail Slider



Special attachment – an inclined plane

Oil refinery - Heater tube

- **Place**: Hyundai Oil in Korea (June, 2001)
- **Object**: #1 CDU HEATER(HS, HF)/ HF-Manifold Reformer Tube
- **Condition**: Comparison of operating time between fresh material and degraded material (Operating time of degraded material: more than 40,000hr / 70,000hr)
- **Material**: ASTM A335 P5/ P9/ P22/ A106/ A376
- **Attachment**: U-block system
- **Remark**: Evaluation of tensile properties with time-dependent degradation



The test subject was heater tube of an oil refinery plant. U-block and V-block were applied depending on the size of the subject. Purpose of the test was the evaluation of aging of the material on use and PQ test of the new material.

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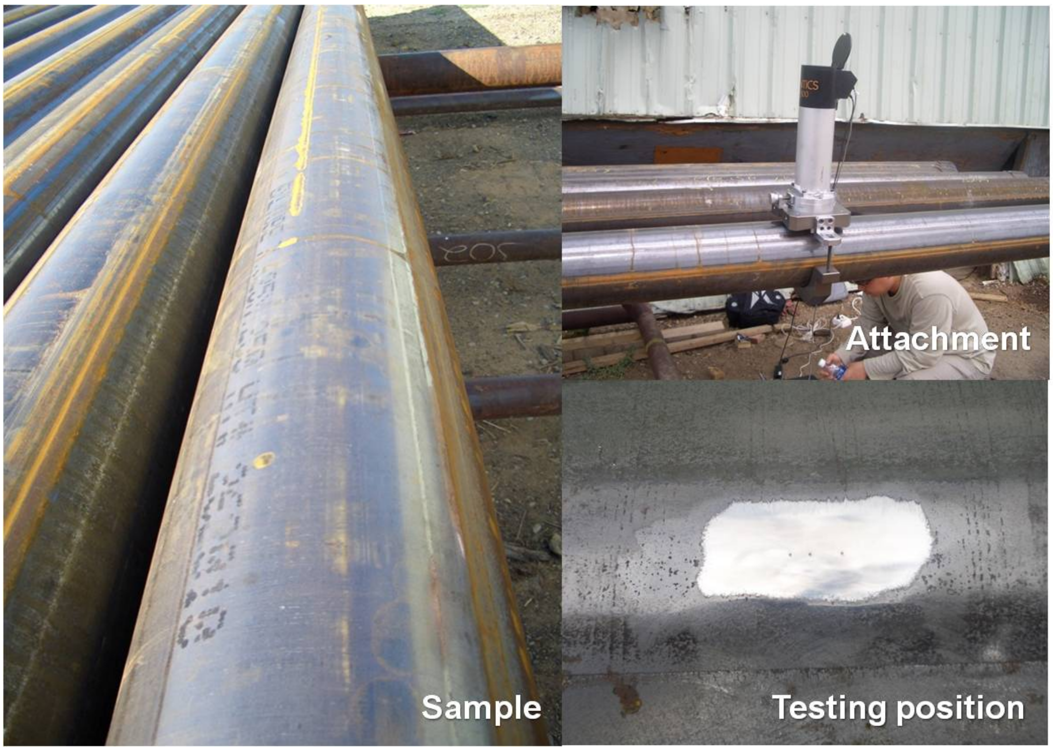
Oil refinery – Freeze tube

- **Place**: Casper, WY, US (in Shell) (August, 2006)
- **Object**: Non-Destructive Yield Strength Measurement of 7.625" Liner for FWT
- **Material**: Freeze tube
- **Attachment**: U-block system

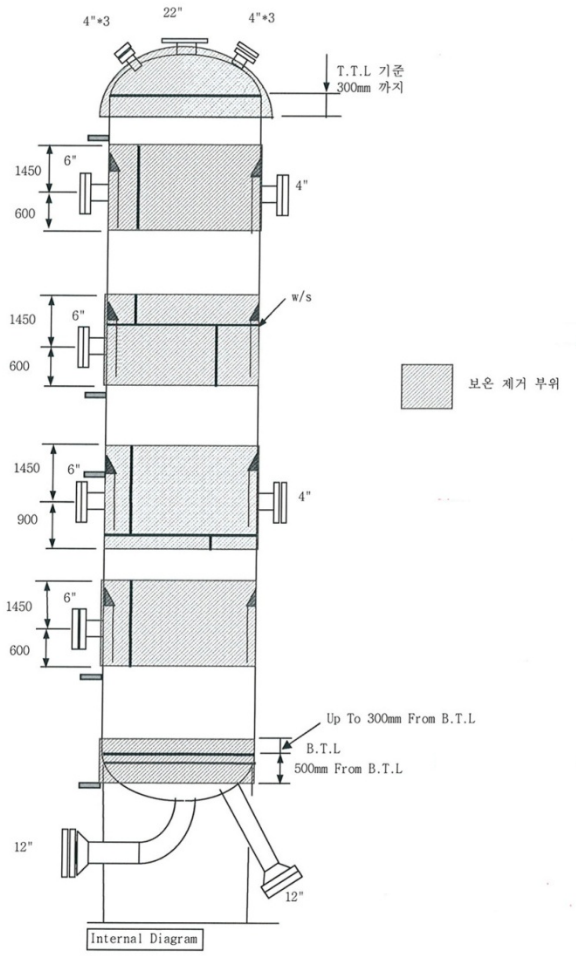


Non-destructive yield stress measurements were performed for the 7 5/8" schedule 20 a mechanical property controlled AXXX grade B line pipes. The test subject was the 1st monitoring of entered pipes (mil cert & CMTR). As can be seen from his comparison, the measured yield strength is within 5% of the mill cert test data. Also shows a comparison between measured data and yield strength from the mill cert (heat number....). Through this testing, time and cost of receiving inspection is reduced.

Oil refinery – Reactor

- **Place**: S-Oil (April, 2009)
- **Object**: Reactor
- **Attachment**: Curvature magnet system

Remark: Evaluation of tensile properties with time-dependent degradation

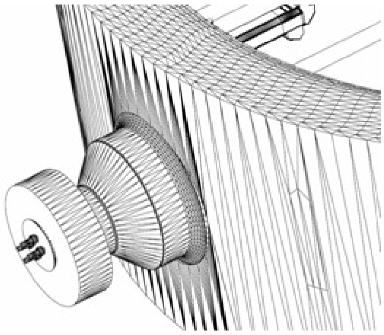
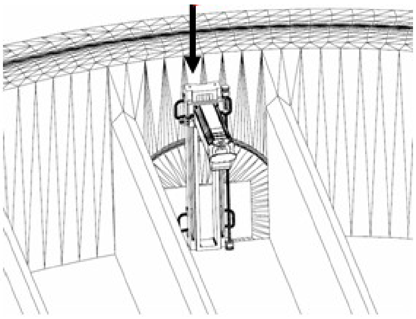
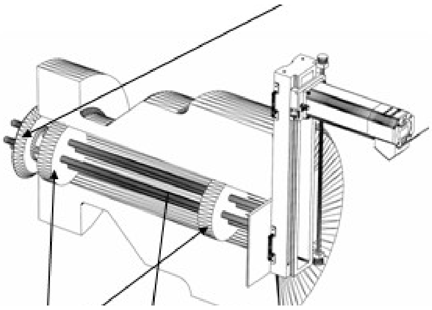
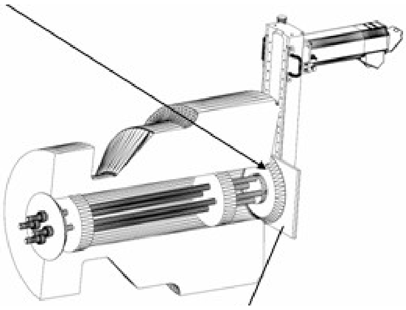


The test subject was reactor of an oil refinery factory, and curvature magnet system was applied, considering the shape. Evaluation of properties of each location and life span evaluation were conducted during the period of overhaul.

Oil refinery – Weld Overlay

- **Place**: SK Energy in Korea (April, 2009)
- **Object**: Weld overlay of Reactor
- **Attachment**: Special attachment system
- **Remark**: Evaluation of tensile properties and safety

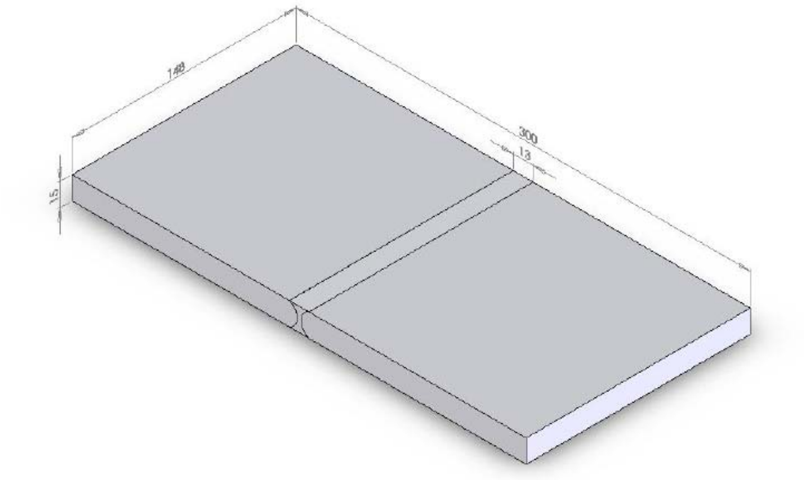


The test subject was the section in reactor where weld overlay had been conducted. Specially fabricated attachment was applied, considering the shape. Purpose of the test was the evaluation of properties and stability of the weld overlay.

Natural Gas Pipeline – Weldment of API X65

- **Place**: Alcoa in US (November, 2007)
- **Material**: API X65 (w/ weld)
- **Attachment**: RS-MPS system
- **Remark**: Evaluation of Tensile properties and residual stress



The test subject was specimen welded with API X65 plate, and we applied RS-MPS that was expansion of MPS, considering the shape. Purpose of the test was to evaluate properties and residual stress of weldment.

Natural Gas Pipeline – API pipe

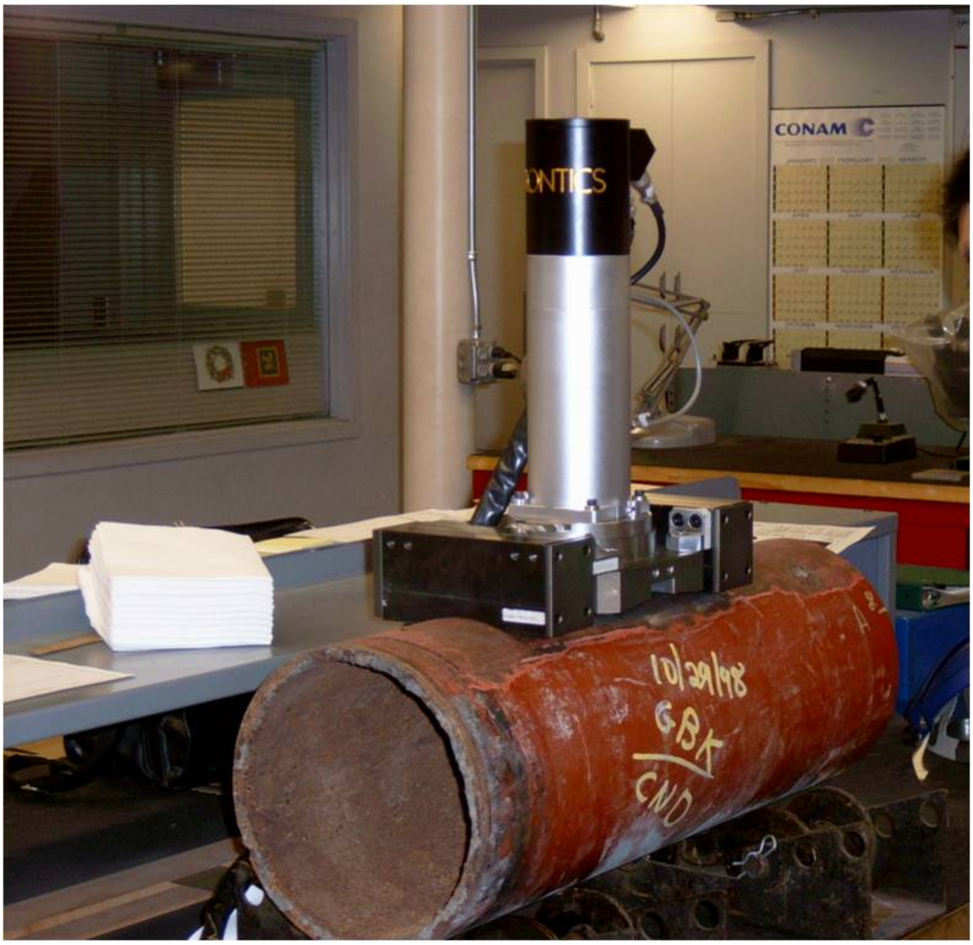
- **Place**: GE Power System (November, 2002)
- **Object**: Natural Gas Line (Mexico)
- **Condition**: Evaluation of tensile properties of underground pipeline
- **Material**: API 5L(API X42, X60, X65)
- **Attachment**: Curvature magnet system
- **Remark**: Underground pipeline of 3M~5M in depth

The test subject was natural gas pipeline that had been installed and operated in Mexico. Considering the shape of the subject, curvature magnet system was applied. The target subject was the exposed pipelines and the underground ones, and aging of the materials was evaluated as well. (Refer to Oil and Gas Journal Vol. 101(2003) pp66-71)

GE Power System (November, 2002)

Natural Gas Pipeline – API pipe

- **Place**: Chevron Texaco (December, 2003)
- **Object**: Natural Gas Line
- **Condition**: Comparison of operating time between new material and degraded material (Operating time of degraded material: more than 20 years)
- **Material**: API 5L pipeline (X65)
- **Attachment**: Curvature magnet system
- **Remark**: Evaluation of tensile properties with time-dependent degradation



The test subject was natural gas pipeline, to which curvature magnet system was applied, considering the shape. Purpose of the test was to compare between the properties of the materials used for over a couple of decades and that of the new material.

2. Application list of Power plant and oil refinery facilities

2001

Ulsan Power plant: Evaluation of tensile properties #4 pipeline (2001.10)
Paul Scherrer Institut (Swiss): Evaluation of tensile properties of Reactor pressure vessel weldment (2001.11)
KOGAS: Evaluation of tensile properties of API 5L weldment (2001.12)

2002

LG Caltex Oil: Degradation evaluation of Vacuum Heater (2002. 2)
Kori Nuclear Power Plant: Evaluation of tensile properties for main cooling water line (2002. 3)
GE Power systems: Evaluation of tensile properties for API X - Houston in-house (2002.4)
Boryong Power Plant: Degradation and safety evaluation of turbine rotor (2002.4)
YoungHeung Power Plant: Evaluation of tensile properties for pipeline (2002. 8)
GE Power systems: Evaluation of tensile properties for LNG pipeline (Underground) - Mexico in-field(2002.11)

2003

Tokyo Gas: Evaluation of tensile properties for High Grade Pipeline (2003. 3)
NKK Corp.(JFE group): Evaluation of tensile properties for Laser weldment of SGP steel (2003. 3)
GE Power systems: LNG Evaluation of tensile properties for LNG pipeline - Mexico in-field(2003. 5)
KEPCO: Evaluation of tensile properties for weldment of SA106C Gr.B (2003. 7)
Himeji Institute of Technology: Evaluation of tensile properties for other friction condition of S35C/ S55C steel (2003. 7)
Osaka University: Evaluation of tensile properties for laser weldment of S35C/ S55C steel (2003. 7)
TWI: Technicla cooperation of TWI (2003. 9)
TWI: Evaluation of tensile properties for Weldment (2003.9)
Huntington Technology: Evaluation of tensile properties for Natural Gas Pipeline API 5L (2003. 11)

2004

Conocophillips: Evaluation of tensile properties for A516-70 and Storage tank (2004. 1)
Chevron Texaco: Evaluation of tensile properties for API 5L (2004. 1)
Canspec (Canada): Evaluation of tensile properties for Cr-Mo steel/ Brittle material (2004. 2)
KEPCO: Evaluation of tensile properties for weldment of STS316L (2004. 6)
KPS: Evaluation of tensile properties for 2.25 Cr-Mo boiler tube with material degradation (2004. 8)
KAERI: Evaluation of residual stress for multi weld of STS316L pipe(2004. 9)
POSCO: Evaluation of tensile properties for API X steel (2004. 9)
KOPEC: Evaluation of tensile properties for dissimilar metal weld(2004. 11)
ExxonMobil: Evaluation of residual stress for other weld condition of API X65 (2004. 11)
ExxonMobil: Evaluation of residual stress for Laser peened effect (2004. 12)

2005

TWI: Evaluation of tensile properties for other weld condition (2005. 02)
SPM, Inc.: Evaluation of tensile properties for Ring flange (2005. 03)
Dangjin Power Plant: Tensile properties Database construction for primary facilities of Dangjin power plant (2005. 3~2006 06)
SAMSUNG TECHWIN: Evaluation of tensile properties for Turbine blade (2005. 03)
GE-PII: Evaluation of tensile properties for API X Gr. (2005. 04)
Ulsan Power Plant: Evaluation of residual stress for Turbine casting, IP rotor, ICV pipe (2005. 05)
EDF: Evaluation of tensile properties for 8 kind materials of power plant facilities (2005. 07)
Sanchun-Yangsu Power Plant: Safety diagnosis of power plant facilities (2005. 07)
ExxonMobil: Evaluation of residual stress for FSW of API(X65, X80) (2005. 09)
Sanchun-Yangsu Power Plant: Evaluation of tensile properties for TBN/Thrust bearing shaft (2005. 09)
ExxonMobil: Evaluation of residual stress for Multi-weld metal (2005. 11)
Gyeongsang Nat'l Univ.: Evaluation of residual stress for dissimilar weld metal (stainless steel) (2005.12)

2006

KEPRI: Evaluation of residual stress for A335 P92 weldment (2006.3)
KEPRI: Comparison of two methods (IIT and X-ray diffraction) for residual stress of A335 P92 weldment (2006.5)
Dangjin Power Plant: Evaluation of tensile properties for aged boiler tube (2006.5)
Shell : Evaluation of tensile properties for API 5C # cashing and tubing pipe (2006.08)
Wolsong Nuclear Power Plant: Evaluation of tensile properties for Turbine material and weldment (2006.8)

2007

FRONTICS-TWI(UK) Project: Evaluation of tensile properties for essential material (10 cases) (2007.1)
Korea Univ.: Evaluation of residual stress for dissimilar weld metal (2007.04)
KIMM: Evaluation of residual stress for dissimilar weld metal with other annealing condition (2007.04)
KGS: Reliability evaluation for pipeline of LG Oil refinery facilities (2007.5)
CJT: Evaluation of residual stress for V-groove weldment (SUS) (2007.11)
Alcoa: Evaluation of residual stress for Plate weldment (2007.11)
KLES: Evaluation of residual stress for dissimilar metal weld (2007.12)

2008

Doosan Heavy Industries & Construction: Evaluation of residual stress for steam generator of power plant (2008.2)
S-Oil: Failure diagnosis and lifetime evaluation for aged 9Cr-1Mo steel (2008.5)
Shell: Evaluation of fracture toughness on the low temperature (2008.6)
Vectren: Evaluation of tensile properties for API (2008.7)
Hyundai Oilbank: Integrity evaluation for weld of valve material (2008.7)
Chosun Univ.: Evaluation of residual stress for SA508, STL316 steel (2008.8)
POSCOSS: Evaluation of residual stress for Forged shell (2008. 8)
KEPRI: Evaluation of residual stress for weld of SUS304 plate (2008. 9)
GTI: Evaluation of tensile properties for API 5L (2008. 10)
POSCOSS: Evaluation of residual stress for Rotor shaft (2008. 11)

2009

Shell (CANADA): Evaluation of low temperature fracture toughness for pressure vessel weldment (2009. 2)
GTI: The reliability evaluation of buried pipeline (2009. 3)
KGS: Evaluation of residual stress for Pohang City Gas Pipeline (2009. 3)
KHNP: Weldability for weld of wall structure in New Kori Nuclear Power Plant #1 (2009. 3~4)
S-Oil: Inspection of Reactor using IIT (2009. 4)
SK-energy: Safety Evaluation for UC-R2103 Weld overlay (2009. 4)
KEPRI: Aging diagnosis for turbine of boryoung power plant (2009. 6)
Shell (USA): Evaluation of fracture toughness for weldment (2009. 6)
Chungcheong Univ.: Evaluation of residual stress for nuclear power plant structure (2009.8)
ExxonMobil: Evaluation of tensile properties for API X80 & X100 HLAW weldmetal (2009. 9)
POSCO: Evaluation of tensile properties for Seamless weld of STS 409L Pipe (2009. 9)
KEPRI: Aging diagnosis for turbine of Dangjin power plant (2009. 10)
ExxonMobil: Flow strength assessment in weldments using Micro Indenter. (2009. 11)
KEPRI: Aging diagnosis for turbine of Taean power plant (2009. 12)

2010

ExxonMobil: Evaluation of nano/micro tensile properties for API X80 HLAW weldmetal (2010. 1)