2.3 Development of PIE Techniques for Irradiated LWR Pressure Vessel Steels

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ABSTRACT

For the evaluation of safety and integrity of light water reactors (LWRs), various post irradiation examinations (PIEs) of reactor pressure vessel (RPV) steels and fuel claddings have been carried out in the Research Hot Laboratory (RHL). In recent years, the instrumented Charpy impact testing machine was remodeled aiming at the improvement of accuracy and reliability. By this remodeling, absorbed energy and other useful information on impact properties can be delivered from the force-displacement curve for the evaluation of neutron irradiation embrittlement behavior of LWR-RPV steels at one-time striking. In addition, two advanced PIE technologies are now under development. One is the remote machining of mechanical test pieces from actual irradiated pressure vessel steels. The other is development of low-cycle and high-cycle fatigue test technology in order to clarify the post-irradiation fatigue characteristics of structural and fuel cladding materials.

1. INTRODUCTION

Mechanical properties of RPV steels and fuel cladding of LWRs at the post irradiation state are the key parameter for the evaluation of safety, structural integrity and lifetime as well as the material development. The mechanical tests at the RHL have been performed for 38 years to support R&D works in this field at JAERI.

The data of Charpy impact test are effectively utilized to evaluate the neutron irradiation embrittlement. Recently, the existing Charpy impact testing machine was remodeled in order to improve its accuracy and reliability.

By this remodeling, absorbed energy and other useful information can be delivered from one-time striking.

In addition, the remote machining technology from actual irradiated RPV steels has been developed in order to clarify the aging behavior of LWRs at the RHL.

Another new technique is developed to determine the post-irradiation fatigue characteristics of structural and fuel cladding materials as low and high-cycle fatigue tests technology with the function as tensile test equipment.

The present paper describes the outline of two mechanical testing apparatuses and techniques and remote machining of mechanical test pieces for irradiated LWR-RPV steels and so on.

2. REMODELING OF CHARPY IMPACT TESTING MACHINE

2.1 Remodeling

The Charpy impact testing machine was redesigned and modified in order to clarify the neutron irradiation embrittlement behavior of LWR-RPV.

This machine instrumented with electronic measuring devices to detect an impact force and a displacement of specimen has an automatic specimen setting system. The block diagram of instrumented Charpy impact testing machine is shown in Fig.1. The load capacity is 300J and it is possible to test in the

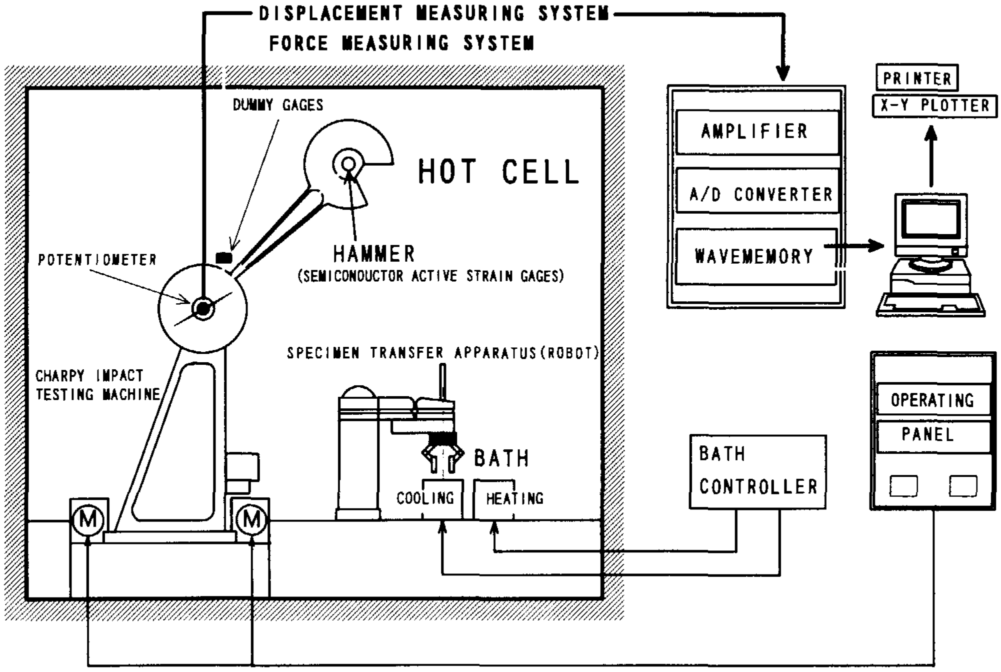


Fig.1 Block diagram of instrumented Charpy impact testing machine

temperature range from -140℃ to 240℃ by using two types of agitated liquid baths. The test specimen is transferred from the cooling (or heating) bath to an anvil of the machine using industrial robot, and struck by a hammer within 4 seconds after removal it from the medium. The test temperature accuracy is within 0.5℃. The test items are V-notch Charpy impact test and K_{Id} dynamic fracture toughness test. The data from Charpy impact test are evaluated on ductile/brittle transition temperature using least squares method, referring a polynomial expression, a hyperbolic tangent and a Gaussian error function. The sensor for the load detection was composed of two semiconductor active strain gages on the tup and two dummy gages put on near the hammer. Moreover, a potentiometer for the displacement detection was inserted and fixed to the hammer shaft. These signals from sensors are recorded in the wave-memory with the capacity of 32Kwords × 2 channels, the resolution of 12bit and the sampling rate of 50~500nsec/word. Collected data are utilized for data processing and analysis.

2.2 Characteristics

A calibration technique is most important in the instrumentation, because it is utilized to convert the data sampled by measuring devices to the force and displacement. The calibration must be carried out in a constant condition that is never affected by a human error and the environment. The RHL developed completely new methods for a load calibration technique as shown in Fig.2. The calibrator can be fastened with positioning and height adjusting to the specimen support on anvils without causing pre-strain to the semiconductor gages pasted on the hammer tup. Therefore, the calibration is possible by the comparison between a proof load from the calibrator and an output of the force-measuring device. In addition, the RHL found that the conversion value should be corrected every time because an output mentioned above changes with a change in ambient temperature. An equation of correction derived from proof tests offers a high accurate conversion value.

On the other hand, the calibration method for the displacement measurement is shown in Fig.3. For the same reason, the calibrator with an electric micrometer is also fixed to the specimen support. Then, calibration is performed by comparing a proof displacement from the calibrator with an output of the displacement-measuring device.

2.3 Performance

An example of obtained data from PIE is shown in Fig.4. A force-displacement curve shows the impact properties during the striking very clearly. The Fgy, Fm, Fu and Fa marked on the curve mean a yield impact force, a maximum impact force, an unstable crack (cleavage crack) initiation force and a crack arrest force respectively. While, the Einst is total impact energy which is area under the complete force-displacement curve. In addition, the curve offers a ductile crack initiation energy, partial impact energy at above points, total displacement of specimen and so on. These impact properties and characteristic values of the points are defined in accordance with ISO standard ISO/DIS 14556[1]. As shown in the figure, the Fgy, Fm and Fu decrease with increasing the test temperature, whereas the Fa increases. The Fa on the curve means a specimen struck in the transition range.

The force-displacement curves obtained from PIE after remodeling are very useful data for the evaluation of irradiation embrittlement.

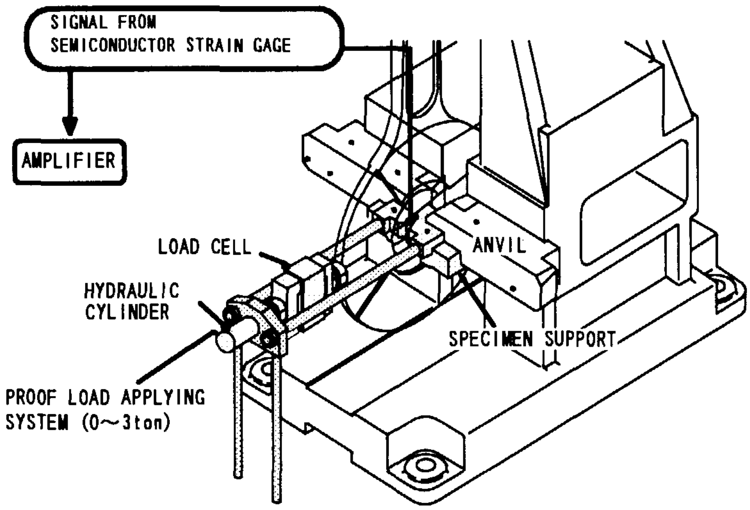


Fig. 2 Force calibrator

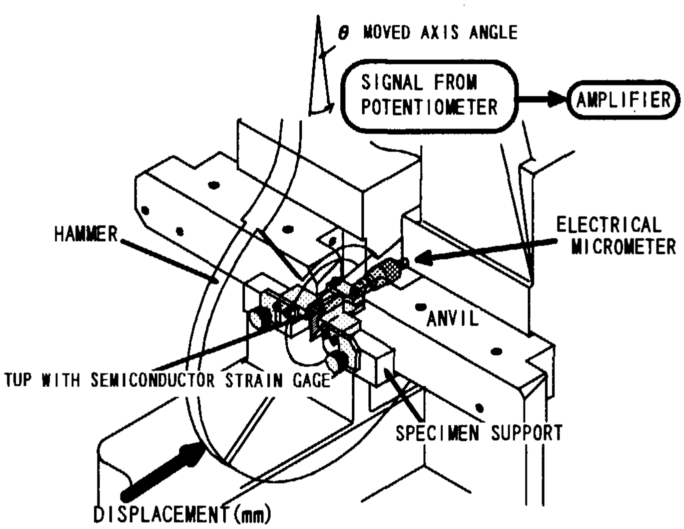
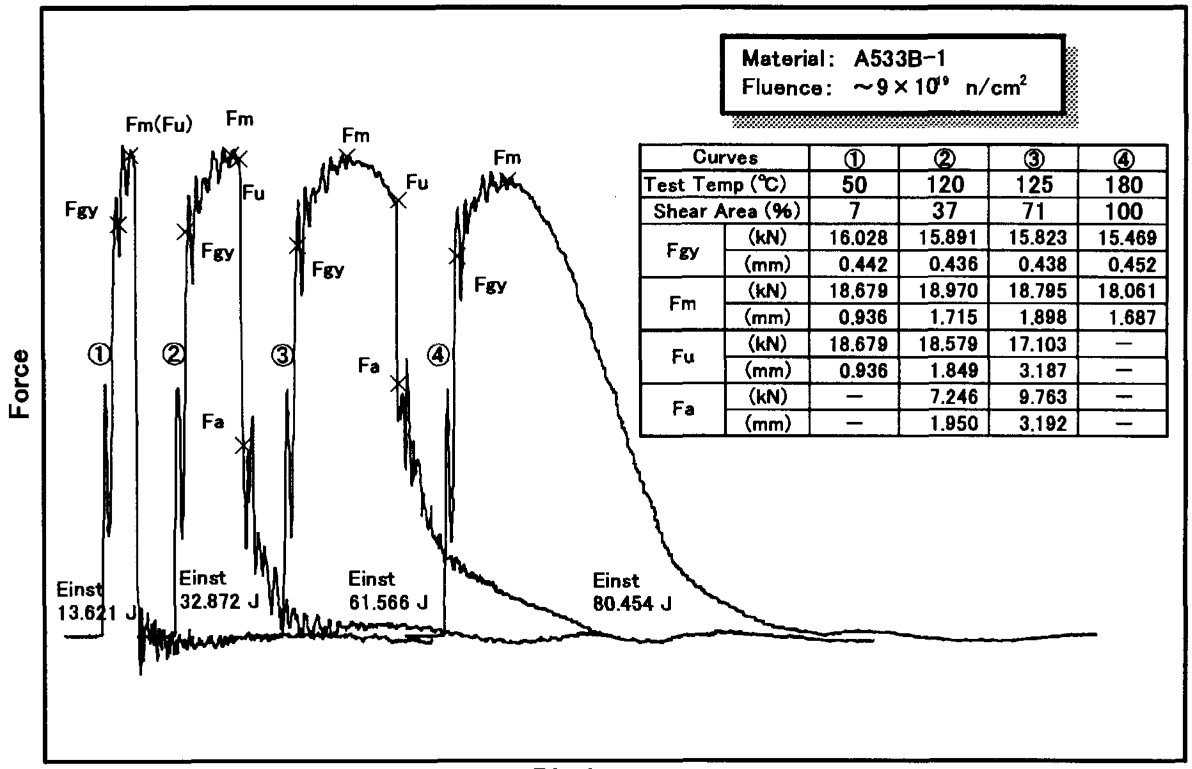


Fig. 3 Displacement calibrator



Curves		①	②	③	④
Test Temp (℃)		50	120	125	180
Shear Area (%)		7	37	71	100
Fgy	(kN)	16.028	15.891	15.823	15.469
	(mm)	0.442	0.436	0.438	0.452
Fm	(kN)	18.679	18.970	18.795	18.061
	(mm)	0.936	1.715	1.898	1.687
Fu	(kN)	18.679	18.579	17.103	—
	(mm)	0.936	1.849	3.187	—
Fa	(kN)	—	7.246	9.763	—
	(mm)	—	1.950	3.192	—

Fig.4 An example of PIE data obtained from remodeled Charpy impact testing machine

3. DEVELOPMENT OF REMOTE MACHINING TECHNOLOGY

3.1 Design concept

In case of irradiated material, since all of manipulation must be remotely handled, machining of the mechanical test specimen should be performed accurately in accordance with the material testing standards such as ISO, ASTM and JIS. However, the remote machining with high accuracy has never been done up to date because the requirement is quite difficult.

Therefore, a numerically controlled machine tool is selected and developed as the most useful apparatus for hot cell work without a human error. As shown in Fig.5, a computerized numerical control (CNC) milling machine developed is composed with the main body for machining and a control system included a personal computer. There are two main bodies produced by same design, which can be operated by an identical controller. One is installed in the hot cell and the other is set up in the operating area for mock-up test prior to in-cell machining.

The original machine for general use is modified according to some requirements from radiation environment, free maintenance and higher performance. Moreover, the innovational techniques are applied to achieve the allowable machining by means of remote handling.

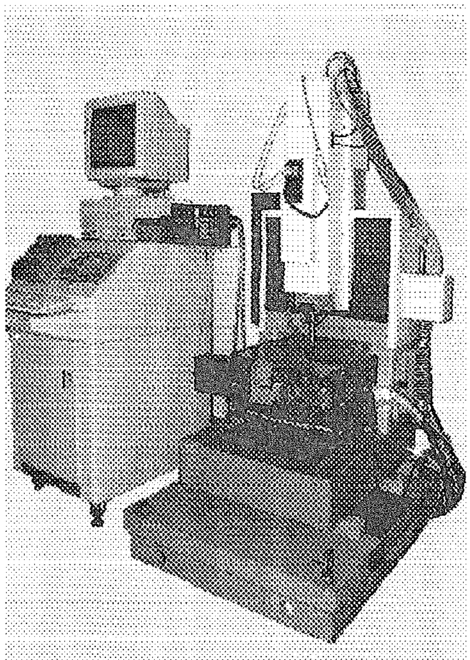


Fig.5 Computerized numerical control (CNC) milling machine

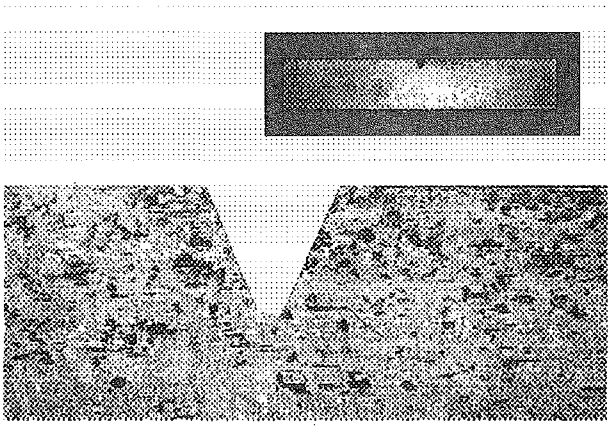


Fig.6 Charpy (type-A) impact test specimen machined by CNC milling machine

3.2 Characteristics and Specification

The CNC milling machine developed is extremely compact of 850×800×1100mm and quite on a par with a general machine tool in mechanical accuracy. In addition, the main body with an automatic tool changer (ATC) included necessary six tools is highly rigid portal structure. The parts reviewed and redesigned are as follows. The motor for X/Y/Z motion was modified from a DC servomotor with rotary encoder to an AC servomotor with resolver. DC servo spindle motor of 200w was also changed to an AC servo of 800w. Then, a magnetic device was selected as the sensors for positioning and the amplifiers were located into control box in operating area. Moreover, the innovational techniques added are as follows.

3.2.1 Clamping mechanism of the work

A clamping mechanism is composed with a hydraulic vise for clamping of a four-cornered work and an electric rotating chuck with AC servo resolver motor combined a bearing which is able to rotate the vice. Therefore, it is possible to machine without re-clamping on five surfaces except bottom of the rectangular work and notch-machining to the top surface.

3.2.2 Automatic measuring mechanism of the origin in Z-motion

In case of a general machine, the origin of Z-motion is manually decided by using a so-called touch sensor, standard gage, which can indicate a contact point of the mill tip and the sensor top. However, decision of the Z-origin with remote handling is not so easy because the largish sensor must be set on a central part of the smallish work. For that reason, the automatic measuring mechanism that is able to detect a contact point through an electrical signal was designed. This idea was accomplished by insulating of spindle using a ceramic coating.

3.2.3 Machining techniques

In general, the tool and work during machining is cooled by plenty of oil, however, the dry machining is the best way, in case of hot cell work, if possible. CNC milling machine in the RHL has an air-cooling system and an intermittent oil-atomizer, which performs the duty as a lubricant rather than a coolant.
The dry machining is achieved by finding out the suitable conditions including kind of machining, selection of tool, machinability of work, cutting and feed speed and so on. Then, an atomizer automatically and periodically sprays cutting oil, if it is necessary.

One of problems in specimen machining of RPV steels is the removing technique of barr (frash) growing on edges. To resolve the problem, the unique mechanism that is utilized CNC milling function is now under development. By this idea, the barr will be removed by a whetstone with automatic operation as a series work of the machining.

3.2.4 Automatic marking technique for identification

To avoid a blunder, the marking for identification should be performed during the machining or immediately after it finished. In addition, the marking must not affect mechanical and metallurgical properties of the specimen. Automatic marking of identification number is possible by combining a pneumatic marking pen with a function of CNC milling machine. The pen is fixed by air chucking with easy handling like a machining tool on ATC magazine. Therefore, the identification number can be automatically marked on the programmed position according to command with key-in.

3.2.5 Dimension measuring system for the machined specimen

The machining error that is the deviation from programmed nominal value is mainly depending on the rigidity and actual diameter of the tool. To compensate the error, the CNC operation program requires the difference between the command and as-machined condition. Therefore, a dimension measuring system utilized CNC milling function was designed. It is composed with two SONY magnescales for measuring the X/Y motions, a touch sensor for commanding the start/end of measuring, a display unit (counter), a resetting jig of the sensor and a holder for combining the sensor with CNC milling body. The sensor is able to touch automatically one side surface and the opposite face of the machined specimen and measures the wide and length.

In addition, the TV monitoring system for confirming the machined notch-shape is now under investigation.

3.3 Performance

The machining programs developed in the RHL are a Charpy impact test specimen type A of 10×10×55(mm) so-called V-Charpy, a plate type tensile test specimen with parallel part of 22.95L×3W×3t(mm), and a three point bending type fracture toughness test specimen with knife-edges. The CNC milling machine is possible to machine these specimens with high accuracy that satisfies the standards, ISO, ASTM and JIS. As one of examples, a machined Charpy impact specimen is shown in Fig.6. For checking of the machining condition, there are a sound sensor and an acceleration sensor on the body. Moreover, a TV monitoring system for observing of tool-edge chipping and chips of work is located nearby the machine.

4. DEVELOPMENT OF REMOTE SYSTEM TECHNOLOGY FOR FATIGUE TESTING

4.1 Fatigue testing machine

One of the important research subjects on the LWR fuel cladding performance at extending burn-up is to understand the mechanical properties. The RHL developed an electro-hydraulic fatigue testing machine with two kinds of load cells and servo valves in tandem and in parallel respectively.

Main load cell with 20KN is used when the maximum load will be more than 2KN for dynamic and 3KN for static loads. Sub load cell with 2KN is utilized for the specimens with lower maximum load than the above-mentioned one. In case of servo valves, the larger valve with discharge rate of 38 l/min is utilized for the high frequency test condition with high load. It is possible to load up to 100Hz. The smaller one with discharge rate of 3.8 l/min is very useful for most of PIEs such as a low frequency test, a lower load test and all of static tests. Therefore, even the tension/compression tests bellow 200N, it is possible with high accuracy. A changing of the signal between the larger ones and the smaller ones can be carried out by manual work at in-cell for the load cells and by switching from out-cell for the servo valves.

By exchanging the test fixtures with remote handling, the machine is utilized for a high-cycle fatigue test with arc-shaped specimen machined from LWR fuel cladding, a low-cycle fatigue test with round specimen from structural materials, a crack propagation test and a high-frequency test. Moreover, tensile test, plan strain fracture toughness test and the fatigue pre-cracking for fracture toughness specimen are also possible. The specification and the performance of fatigue testing machine are shown in Table.1.

4.2 Characteristics

The alignment of load train including a specimen is the most important in the fatigue test. ASTM standard [2] recommends that the bending moment during the full-reverse testing should be maintained within 5% of axial load. This is not so easy even a general test. The developed fixturing technique is able to make sure the allowable alignment every time with easy operation in spite of remote handling using manipulators. The fixturing way for the RHL fatigue testing machine is as follows.

In case of a arc-shaped specimen with parallel part of 2.5w × 5L × 0.7t (mm) that has very poor rigidity, the specimen is fastened with volts to upper and lower test fixtures by means of an assembling device which is able to tighten uniformly and constantly with easy operation using manipulators. The upper and lower fixtures connected and reinforced by the support handle are placed into the sockets of pull rods. Finally, both fixtures are held by the hydraulic clamping system. Because of that, the specimen can be fixed without a significant pre-strain. On the other hand, a round type specimen with parallel part of ϕ 4 × 8L × G.L6(mm) is inserted by manipulator directly into the upper and lower fixtures installed in socket and pressed and fixed by the hydraulic clamping system. As mentioned above, the fixturing technique developed is very easy and never requires the particular handling. However, in case of the round specimen, the fixture technique requires a superior specimen with the accuracy of 0.005mm in cylindrically deviation and parallelism deviation between end surfaces. As the result of that, the bending moment from low-cycle full reverse fatigue test can be hold within 5% of the axial load. Gripping and setting for the static tests are also conducted easily by similar method. The excellent alignment can be readjusted by using an alignment measuring system, which consists of a verification bar with four strain-sensing devices, a display and analysis apparatus for local strains. And the adjusting can be carried out with cautions of handling and with monitoring the rectangular coordinates chart on CRT in real time, which indicates the four local strains on the bar during the handling.

Table.1 Specification and performance of fatigue testing machine

① Type of machine	Fatigue testing machine equipped with electro-hydraulic servo actuator SHIMADZU EHF-ED20KN-20LA
② Capacity	Load frame ; ±100KN(dynamic load)
	dynamic load , static load
③ Performance	Main load cell ; ±20KN , ±30KN
for high-load	Sub load cell ; ±2KN , ±3KN
for low-load	Load range ; ±0.2 to 20KN, ±0.2 to 30KN
	Frequency range ; $10^{-5}\sim10^{2}$ Hz
	Actuator speed ; $1.56\times10^{-5}\sim10^{3}$ mm/sec
	; $6.25\times10^{-7}\sim6\times10^{2}$ KN/sec
④ Utilization	Tension/compression tests as follows,
for mechanical tests	Fatigue test (full-reverse);
	High-cycle and low-cycle fatigue tests
	crack propagation test and high frequency test
	Static test ; Tensile & plan strain fracture toughness tests (unloading compliance method)
for preparation work	Fatigue pre-cracking for fracture toughness specimen
⑤ Test conditions	Temperature; -140～450℃ in temperature chamber
	Atmosphere ; air
	Alignment ; Bending strain during the full-reverse fatigue test is within 5% of axial strain
⑥ Specimen	Round specimen with button head connection(standard)
for fatigue test	Overall length ; 44 mm
	Parallel part ; ϕ4×8 mm , G.L 6 mm
	Shoulder radius ; R15.6mm
	Arc-shaped specimen taken from LWR fuel cladding
	Total length ; 40mm
	Parallel part ; 2.5W×5L×0.7T mm
for tensile tests	Round specimen ; PP.ϕ4×22,0L55 mm
	Arc-shaped specimen; PP.2.5W×15L×0.7T,0L40 mm
	PP(parallel part)
for fracture	CT type ; 0.4CT, 0.5CT, 0.63CT
toughness test	DCT type ; 0.4DCT, 0.5DCT, 0.63DCT
pre-cracking	3-points bending fracture toughness specimen

4.3 Performance

In case of an arc-shaped specimen, the fastening torque of 10.3 N-m for inside volts and 39.2 N-m for outside volts makes suitable test condition. These values obtained from experiments are accurately controlled every time by using the torque meter with strain gage. With regard to the cycle frequency, it is possible to utilize up to 40Hz. This is good performance, because even a test up to 10^{7} cycles, it is achieved only within 3 days. Fig.7 shows a plot of data from the RHL machine and from a literature [(3)] on unirradiated Zry-2 specimen. Test was performed with cycling frequencies of 3 to 40 Hz and with a stress ratio of $R=\sigma_{min}/\sigma_{max}=-1$ at room temperature, and loading stress of ±164 to ±492 Mpa with sine wave. As shown in figure, the fatigue lives from the RHL machine agree with the reference values which were taken by the standard testing method, in spite of an arc-shaped cross section of an imperfect symmetry.

On the other hand, the low-cycle fatigue test results with a ϕ4 round specimen of Hastelloy XR-II agree quite well with the conventional test specimen of parallel part of ϕ 10×20L(mm) .

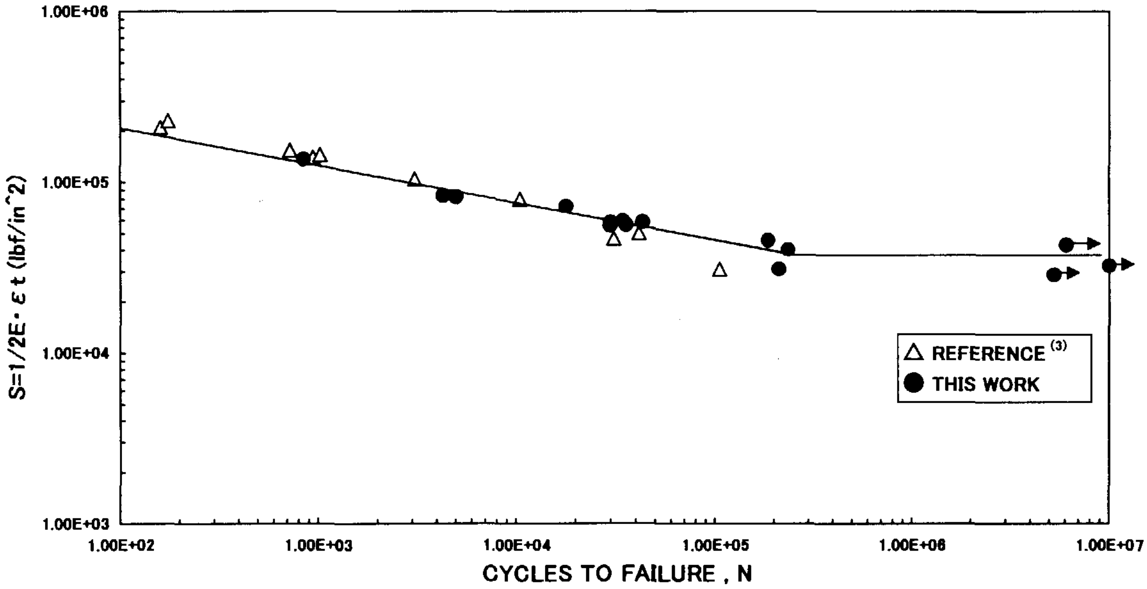


Fig.7 Fatigue data on unirradiated Zry-2 (at room temp.)

5. CONCLUSION

By remodeling of Charpy impact testing machine, absorbed energy and other useful information on impact properties can be delivered from the force-displacement curve for the evaluation of neutron irradiation embrittlement behavior of LWR-RPV steels at only one blow of a hammer.

Development of the CNC milling machine makes possible not only machining of mechanical test specimens from actually irradiated structural materials but also converting the Charpy V-specimen irradiated into a fracture toughness specimen. The establishment of this technique with fatigue pre-cracking will contribute to more precise life evaluation of RPV steels in LWRs by utilizing the surveillance specimen.

With regard to development of the fatigue testing technology, it was proved that developed fatigue testing machine and its technique offer the valid results in high-cycle and low-cycle fatigue tests with full-reverse loading. The high-cycle test technique developed will be utilized to evaluate the fatigue property in high-burnup program for LWR fuel in near future. The low-cycle test technique using a round specimen is the most useful and will be used in R&D works of the structural materials for the future.

6. ACKNOWLEDGMENTS

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7. REFERENCES

(1) INTERNATIONAL STANDARD ISO/DIS 14556(draft)
Steel-Charpy V-notch impact test-Instrumented test method, (1998)

(2) ASTM Designation: E606-92
Standard Practice for Strain-Controlled Fatigue Testing, (1996)

(3) W.J.O'Donnell and B.F.Langer: Fatigue Design Basis for Zircaloy Components, NUCLEAR SCIENCE AND ENGNEERING, 20,1-12(1964)