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FBR Metallic Materials Test Manual (English Version)

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Abstract

For the development of the fast breeder reactor, this manual describes the method of in-air and in-sodium material tests and the method of organization the data. This previous manual has revised in accordance with the revision of Japanese Industrial Standard (JIS) and the conversion to the international unit. The test methods of domestic committees such as the VAMAS (Versailles Project on Advanced Materials and Standards) workshop were also referred. The material test technologies accumulated in this group until now were also incorporated. This English version was prepared in order to provide more engineers with the FBR metallic materials test manual*2.

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＊2 JNC TN9520 2001-001 FBR Metallic Materials Test Manual (Revised Edition)

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1. Introduction

Our group has conducted various material tests on SUS 304 and 2¼Cr-1Mo steel used as structural materials for the FBR(Fast Breeder Reactor)Monju, and the test results were reflected in the formulation of "Elevated Temperature Structural Design Strategy Guide for class 1 components of Prototype Fast Breeder Reactor, material strength standards, etc" [1] . Since then, we have tested 316FR and Modified 9Cr-1Mo steel, which are candidate materials for the next generation large-scale reactor, and have successfully obtained data necessary for the development of elevated temperature structural design technology.

In 1977, "FBR Metallic Material Test Manual" [2] was prepared to standardize the methods of material tests performed for the development of fast reactors, as well as the procedure to organize the test results. This manual is the revision of the above "FBR Metallic Material Test Manual", in response to the changes made in Japanese Industrial Standards (JIS) regarding test methods and the adoption of International System of Units (SI). Also, this manual was created in view of the material testing method trends at national committees, including VAMAS (Versailles Project on Advanced Materials and Standards) low cycle fatigue research group of Iron and Steel Institute of Japan [3] . In addition, to pass on material testing techniques, this document summarizes the testing techniques our group has acquired.

2. Material Testing Procedures

2.1 Tensile test

2.1.1 Range

The rules described in this chapter shall apply to the tensile test for FBR metallic materials.

2.1.2 Definition of terms

Table 2.1-1 shows the definition of terms used in this test.

Definition of terms (common) used in welding are listed in Appendix 2.1-1.

As for unit notation, the International System of Units (SI) is used.

2.1.3 Test pieces

Test pieces used for this test shall generally comply with JIS G 0567 and JIS Z 2201.

The gauge length (GL) shall be the distance between the inner ends of the collars.

Test materials include plates, forgings, pipes, bars, etc, which have a uniform metal structure for fast reactor structural materials, as well as welded metals and joint materials.

(1) Test piece shape

As shown in Figure 2.1-1, the test piece shall generally be of round cross section, and the standard test piece shall be a solid round-bar shape with collars. The diameter of the parallel portion shall generally be 10mm, but 6mm, 8mm or 12mm diameters may be used. The length of the test piece parallel portion shall be 5D (D: diameter of the parallel portion), which will be the gauge length.

Also, if a test piece with a circular cross section cannot be obtained, a plate test piece or arc section test piece cut form pipe (heat exchanger pipe) in the axial direction can be used.

Using test pieces of shapes and dimensions other than that of the standard test pieces shall be discussed and determined separately.

(2) Sampling positions

Test pieces should be arranged so that their axial direction and the material finishing direction (roll direction, extrusion direction, and main forging direction) are parallel. In addition, depending on the research objective (evaluation of anisotropy, etc), samples can be arranged in a perpendicular direction or board thickness direction. This sampling method, however, does not apply to weld metals and joint materials. The position, direction and processing method of test pieces must be clearly recorded.

(3) Processing method

① Processing of the test piece is shown in Figure 2.1-2. Tolerance of outside diameter of the parallel portion must be ±0.01mm or less, and basically the center of a test piece must be maintained.

② The parallel portion of the test piece must be polished in axial direction with emery paper (600 or above) so that there will be no sharp angle scratches in the circumferential direction (lathe defects). Also, the test piece should be adequately cooled to minimize surface residual stress, and should be processed gently and slowly. Surface roughness in the maximum main stress direction shall be 1.6 μm or less ideally.

③ A plate test piece and an arc section test piece will be processed by wire cutting or machining. Machined surfaces should be polished with emery paper (600 or above).

(4) Manufacturing of special test piece

Figure 2.1-3 shows an example of manufacturing weld metals and joint tensile test pieces form the narrow groove weld joint.

2.1.4 Testing apparatus

Testing apparatus for this test must comply with JIS B 7721 and JIS G 0567, and an extensometer must conform to JIS B 7741.

Testing apparatus consists of a main test unit, an instrument for measuring elongation, a heating device, and a recording device. Specifications of the testing apparatus installed in our group are shown in Appendix 2.1-2 and its configuration is shown in Appendix 2.1-3.

(1) Main test unit

The main test unit shall be of the grade 1 of JIS B 7721 or higher .

This unit consists of a loading instrument that exerts load onto the test piece, a cross head controller that stabilizes the loading rate, and a load sensor (load cell) that measures the load. Accuracy of measuring load shall be within ±1.0%, and crosshead speed accuracy shall be within ±0.1%.

(2) Test piece grip (chuck)

The grip shall be shaped to ensure the center of a test piece and shall be constructed so that forces other than the tensile force are not applied.

For round-bar type test pieces, a screw type grip is ideal, while the pin grip is preferred for the sheet and arc section test pieces. The materials of the grip shall be heat-resistant alloys such as Inconel 718.

Appendix2.1-4 shows an outline of a test piece grip.

(3) Instrument for measuring elongation

The instrument to be used to measure elongation of the test piece in the axial direction shall conform to JIS B 7741 grade 1 or higher.

Elongation between the gauge marks of the test piece will be measured by instruments such as an arm shoulder type extensometer (refer to Figure 2.1-4).

(4) Heating device

An electric fire heating furnace system is preferred as the heating device. A thermocouple for detecting temperatures shall comply with JIS C 1602, and R thermocouple with 0.5 ϕ diameter (JIS class – 2) shall be used for up to 900℃ as the standard, while B thermocouple with 0.5 ϕ diameter (JIS class – 2) shall be used between 900 and 1600℃. In addition, the PID adjustment system shall be used to control temperature.

(5) Recording device

To measure stress, strain, and temperature, recorders or online data collection systems shall be used.

① Recorder

The X-TY recorder shall be used to record load and elongation between the gauge marks, and the temperature recorder shall be used to record the changes in temperature over time.

② Online data collection system

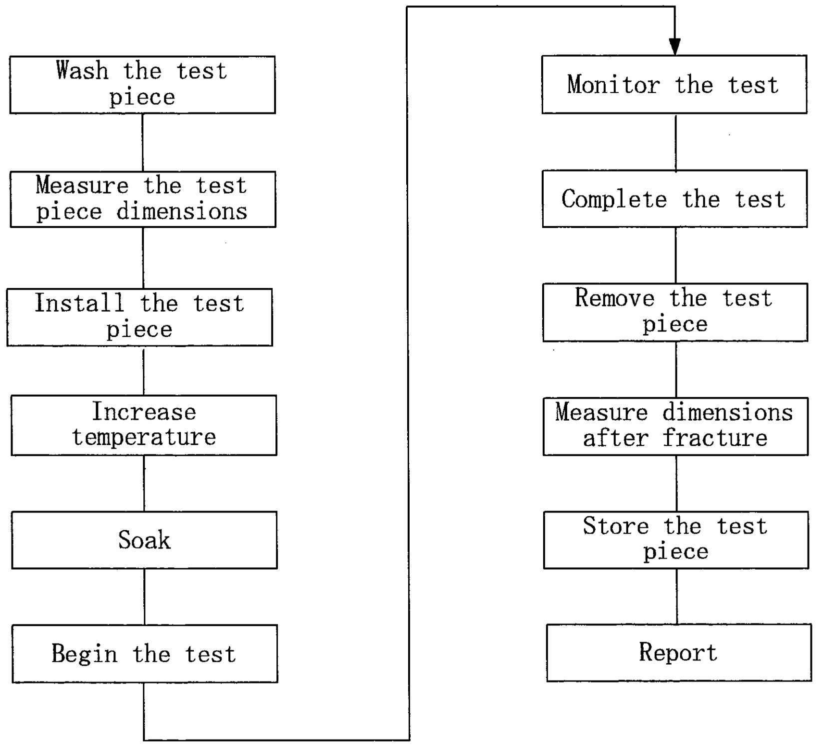
This system is used to measure tensile test data, and to calculate tensile characteristics from the measured data.

Appendix 2.1-5 shows the configuration of an online data collection system.

2.1.5 Test methods

Test temperature, loading method, and measurement method of elongation and load shall comply with JIS Z 2241 and JIS G 0576.

Standard test procedures for the tensile test are shown below.



(1) Washing the test piece

The container for washing should be large enough so that the entire test piece can be submerged during washing. Using the ultrasonic washing machine, clean the test piece in a drafter, first by acetone and then by ethanol for 10 minuets each.

After washing, store the test piece in a desiccator to protect against rusting.

(2) Measuring the dimensions of the test piece

① Measuring the round-bar test piece

To obtain measurements between the gauge marks (GL) and between collars (F) of the test piece, use tools such as a projection device, and take the measurements twice, as shown in Figure 2.1-5, at a 180 degree direction with the punch mark as the origin. Also, to measure the diameter, use a micrometer and take the measurements twice at a 90 degree direction at three positions of A, B, and C. During measurement, care should be taken not to damage the parallel portion of the test piece.

The cross-sectional area used in stress calculation shall be calculated by averaging the values at 6 measurements (three positions of A, B and C x 2 times).

② Measuring the sheet test piece

Measurements between the gauge marks (GL) and between collars (F) of the test piece shall be taken using the same process as for the round-bar test piece. As shown in Figure 2.1-5, use a micrometer to measure the thickness and the width, and take measurements at the center of the three positions of A, B and C of the test piece.

A cross-sectional area used in stress calculation shall be calculated from the average of the three positions of A, B, and C.

③ Measuring the arc-form test piece

Measurements between the gauge marks (GL) and between collars (F) of the test piece shall be obtained using the same process as for the round-bar test piece. As shown in Figure 2.1-5, thickness and width measurements shall be taken using the same process as for the plate-form test piece. However, when measuring thickness, use a micrometer that has a ball-shaped tip, as a conventional micrometer may cause a gap.

The cross-sectional area used in stress calculation shall be calculated from the average of the three positions of A, B, and C. Here, the cross-sectional area of the arc-form test piece shall be obtained from the formula shown in Appendix2.1-6.

(3) Installing the test piece

When installing the test piece, care should be taken to avoid applying torsion or bending load to the test piece.

(4) Heating method

Using the heat resistant cord, tie two thermocouples at both ends of the parallel portion of the test piece, and the third thermocouple at the center of the parallel portion of the test piece. Heat the test piece by an electric furnace, etc, and adjust the temperatures at the three thermocouples to be within the target range shown in Table 2.1-2. As shown in Figure 2.1-6, the tip of the thermocouples (temperature detecting part) shall be a ball-shape. Also, by covering the tip of the thermocouple with a heat-resistant cord, measurement errors due to radiation heat from the furnace wall can be avoided (refer to Figure 2.1-7).

When heating the test piece, care should be taken not to exceed the test temperature. After reaching the test temperature, maintain the test piece to achieve a uniform temperature distribution about 15 minutes before beginning testing.

Thermocouples shall be replaced with new ones before 1×10^4 hours of use, based on the effects of temperature and time on deterioration of R thermocouples [1] .

(5) Loading method

The loading method shall be a strain control between the gauge marks of the test piece.

During the test under the strain control, if the test piece is not fractured even if output of the elongation detector (25mm/F.S) exceeds 90%, change to the crosshead control and continue testing.

Loading rate as a rule shall be 0.3%/min from the beginning to 1% or 3% strain, and 7.5%/min thereafter.

Here, to remove the clearance of the loading jig, etc, be sure to exert an initial load (about 25kg) before starting the test.

(6) Tensile test data

To determine characteristics of each tensile, measure and record the stress-strain curve continuously by an X-TY recorder.

Also, if equipped with an online measurement system, it is recommended to collect data every 0.10 to 0.20 seconds for the low rate area (0.3%/min), and every 0.5 to 1.00 seconds for the high rate area (7.5%/min)

(7) Measuring dimensions after fracture

① Measuring the round-bar test piece

Use the projection apparatus, etc, to measure the dimensions of the test piece after fracture. Fractured test pieces shall be fitted back together as shown in Figure 2.1-8. To obtain measurements between collars (F'), measure the test piece twice in a 180 degree direction starting at the punch mark portion. To obtain measurements between the gauge marks (GL') of the test piece, calculate using the formula [GL'= F'-(F-GL)] to avoid measurement errors. To measure the diameter, measure the smallest fitted region point A, twice in a 90 degree direction. At this point, fixing the test piece by clay, etc, will facilitate the operation. When fitting the test pieces back together, care should be taken not to damage the fractured section.

② Measuring the sheet-form test piece

As shown in Figure 2.1-8, measurements between collars (F') and between the gauge marks of the test piece shall be taken using the same process as for the round-bar test piece. The minimum cross-sectional area shall be the smallest fitted area (thickness x width). The reduction of area calculated from the minimum cross-sectional area shall be reference data.

③ Measuring the arc-form test piece

As shown in Figure 2.1-8, measurements between collars (F') and between the gauge marks of the test piece shall be taken using the same process as for the round-bar test piece. The process to calculate the minimum cross-sectional area shall be same as for the round-bar test piece. Here, the reduction of area calculated from the minimum cross-sectional area shall be reference data.

Also, as a special case, one method to calculate the test piece is by tracing the cross-sectional area with projection apparatus and calculating by an image processor.

(8) Determining the fracture location

As shown in Figure 2.1-9, areas between gauge marks shall be divided into four sections for the fracture locations of base materials and welded metal test pieces; two sections in the center shall be A, each section next to these two sections shall be B, and the area outside the gauge marks shall be C. The categories of A, B, and C, can be classified based on the length between gauge marks after fracture.

In case of the welded joint test piece, fracture locations (welded metals (WM), boundary (BOND), head affected zone (HAZ), or base material (BM)) are determined by observing metal structures, etc, after fracture.

Also, for dissimilar material joints, the type of fractured steels shall be indicated.

(9) Storing the test piece

After dimension measurements, wrap each test piece with paper towel, etc, label the test piece number, test conditions, etc, and store it in the designated desiccator.

2.1.6 Report of test results

The following items shall be reported as tensile test data. Typical datasheets and graphs are shown in Appendix 2.1-7 and 8.

(1) Name of material (type of steel, heat No.)
(2) Quality and shape of the test piece (including the past records of the test piece)
(3) Detailed specifications of the testing apparatus
(4) Test conditions
 ① Test temperature
 ② Test control
 ③ Test speed
 ④ Strain when switching the test speed
(5) Test method
(6) Test results
 ① Apparent Elastic Modulus
 ② Proportional limit
 ③ Yield point or yield strength (0.2%)
 ④ Ultimate Tensile Strength
 ⑤ Uniform Elongation
 ⑥ Fracture Ductility (Fracture Elongation, strain)

⑦ Fracture locations

⑧ Nominal stress — strain curve, true strain – tree stress curve, etc.

(7) Others, presence or absence of aberrance that occurred during testing

2.1.7 Adding the test results to the database

Test results shall be entered into SMAT (FBR Structural Material Data Process System). Appendix 2.1-9 explains the outline of SMAT. By using SMAT, material strength data shall be reported in the form of a datasheet as needed.

2.1.8 Normative reference

① JIS B 7721-1997 Japanese Industrial Standard (JIS) Verification of the force measuring system for tensile testing machines

② JIS B 0031-1994 JIS Technical drawings - Method to indicate surface texture on drawings

③ JIS B 0601-1994 JIS Surface roughness - definitions and designations

④ JIS B 7741-1999 JIS Verification of extensometers used in metallic material tensile testing

⑤ JIS C 1602-1995 JIS Thermocouples

⑥ JIS G 0202-1987 JIS Glossary of terms used in iron and steel (testing)

⑦ JIS G 0567-1998 JIS High temperature tensile testing methods for steels and heat-resisting alloys

⑧ JIS Z 2201-1998 JIS Test pieces for tensile testing of metallic materials

⑨ JIS Z 2241-1998 JIS Tensile test methods for metallic materials

⑩ JIS Z 3001-1999 JIS Welding terms

⑪ JIS Z 3121-1993 JIS Tensile testing methods for butt welded joints

⑫ JIS Z 8401-1999 JIS Standards for rounding off of numerical values

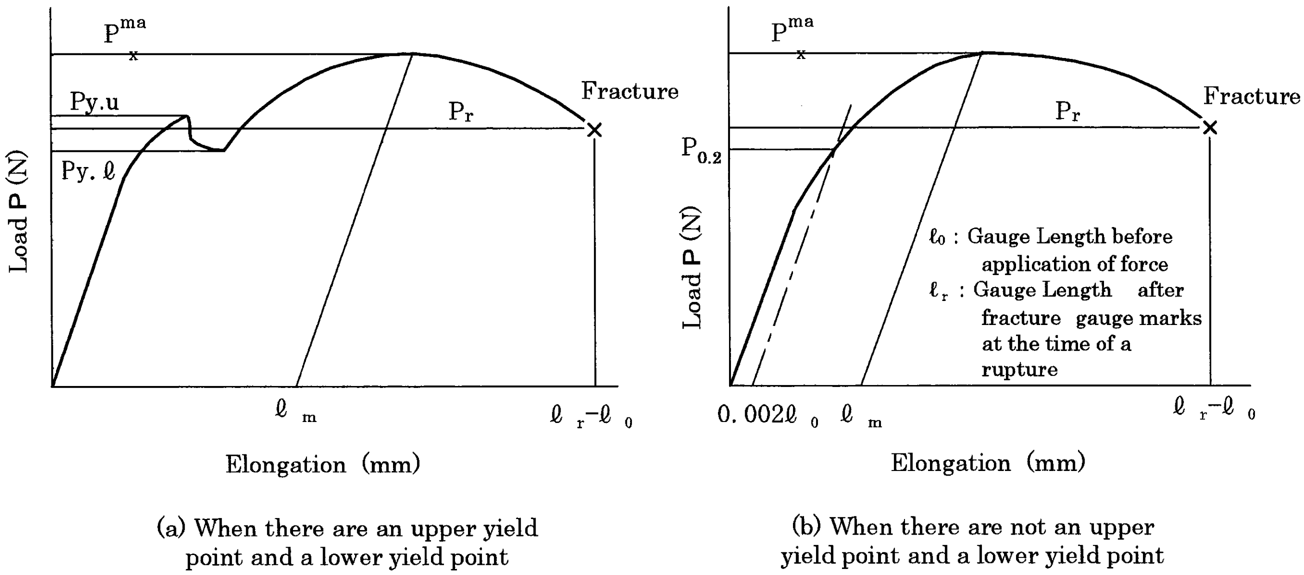
※ For normative references without year of publication, the most recent edition applies.

Table 2.1-1 Definition of terms for tensile test

No.	Terms	Standard symbols (Unit)	Descriptions
1	Test Temperature	T (℃)	Average temperature during the test
2	Nominal Strain Rate	ε (%/min)	When average nominal strain rate between gauge marks, or the strain between gauge marks cannot be measured, this value is calculated from the displacement between crossheads as corresponding rate.
3	0.2% Offset Yield Strength	$\sigma_{0.2}$ (N/mm^2)	Stress ((N/mm^2)) is calculated according to the load-elongation diagram using the extensometer, by drawing a line parallel to the straight line portion in the early stage of the test from the point equal to 0.2% of the gauge length on elongation axis, as shown in the attached figure 2.1-1, and then dividing the load $P_{0.2}$(N) at the intersection of this line and the curve with the original cross-sectional area A_0(mm^2) of the parallel portion of the test piece. $\sigma_{0.2}=P_{max}/A_0$
4	Ultimate Tensile Strength	σ_B (N/mm^2)	Stress is calculated by dividing the maximum tensile load P_{max} from the load-elongation diagram with the original cross-sectional area of parallel portion A_0, as shown in the attached figure 2.1-1. $\sigma_B=P_{max}/A_0$
5	Uniform Elongation	ε_{unif} 1) (%)	The limit value of the eternal elongation since the parallel portion of the test piece will distort almost uniformly, is calculated as the eternal elongation versus the maximum tensile load (refer to the attached figure 2.1-1). ε_{unif} 1)$=\ell_m/\ell_0\times100$(%)
		ε_{unif} 2) (%)	Calculated by using the following formula- A' is the cross-sectional area located far from the fractured portion, and A is the original cross-sectional area of the parallel portion. This value is calculated only when required. ε_{unif} 2)$=(A-A')/A'\times100$%
6	Fracture Elongation	δ (%)	Calculated by matching the gauge length after fracture ℓ minus the original gauge length ℓ_0, divided by ℓ_0 (refer to the attached figure 2.1-1). $\delta=(\ell-\ell_0)/\ell_0\times100$(%)
7	Reduction of Area	ϕ (%)	calculated as the original cross sectional area of the parallel portion of the test piece A_0 minus the minimum cross-sectional area A of the fractured portion, divided by A_0.. $\phi=(A_0-A)/A_0\times100$(%)
8	Apparent Elastic Modulus	E_a (N/mm^2)	Calculated by least-squares method using values within the range of the upper and lower limits of the straight line portion of the early state of the test in the load-elongation diagram

Table 2.1-1 (continues) Definition of terms for tensile test

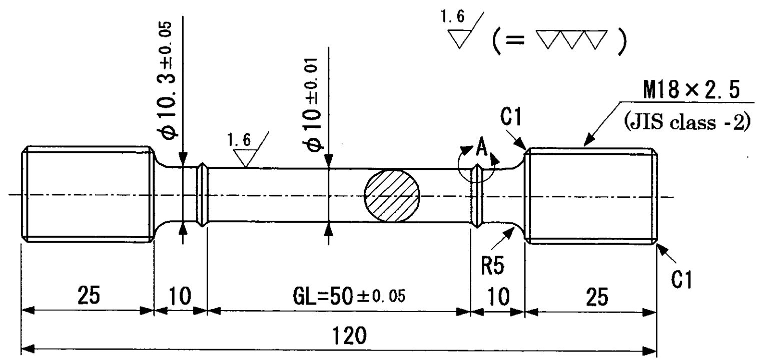
No.	Terms	Standard symbols (unit)	Descriptions
9	Fracture Location	—	Normally shown as A, B, and C, signifying the relative relationships between gauge marks and the center at the time of fracture. This specification method is shown in Figure 2.1-9 (in accordance with JIS Z 2241). For welded joints or dissimilar material joints, descriptions in 2.1.5(8) apply.
10	Yield Point	σ_y	Yield point is the stress at which the test piece yields due to the sliding phenomenon. The starting point of yield is called upper yield point (P_y. u/A_0), and the point when the yield process progresses is called lower yield point (P_y. ℓ/A_0), as shown in attached figure 2.1-1.
11	Elongation in 4 D	δ_{4D} (%)	Fracture elongation when the gauge length is 4D. Calculated only when required.
12	True Fracture Stress	σ^*_f (N/mm^2)	Calculated by dividing the fracture load P_r with the minimum cross sectional area A of the fractured portion (refer to attached figure 2.1-1). $\sigma^*_f = P/A$
13	Nominal Stress	σ (N/mm^2)	Calculated by dividing the load P of each targeted stage with the original cross-sectional area A_0. $\sigma = P_r/A_0$
14	Nominal Strain	ε (%)	Calculated by subtracting the original gauge length ℓ_0 from the gauge length of each targeted stage , divided by ℓ_0. $\varepsilon = (\ell - \ell_0)/\ell_0 \times 100(\%)$
15	True Stress	σ^* (N/mm^2)	Calculated by dividing the load P of each targeted stage with the minimum cross-sectional area. $\sigma^* = \sigma(1 + \varepsilon/100)$
16	True Strain	ε^* (%)	Strain is calculated by using the gauge length of each targeted stage as the standard. $\varepsilon^* = \ell n(1 + \varepsilon_{unif}/100) \times 100$
17	True Uniform Elongation	ε^*_{unif} (%)	Uniform elongation in calculated by using the gauge length of each targeted stage as a standard. $\varepsilon^*_{unif} = \ell n(1 + \varepsilon_{unif}/100) \times 100$
18	True Fracture Ductility	ε^*_f (%)	True strain at the time of fracture. $\varepsilon^*_f = \ell n(100/100 - \phi) \times 100$ Here, ϕ denotes the reduction of area.

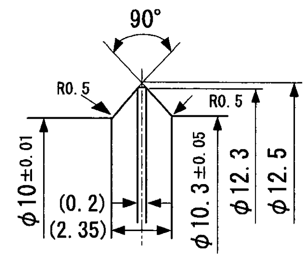


Reference Fig. 2.1 General example of load-elongation diagram

Table 2.1-2 Target range of test temperature

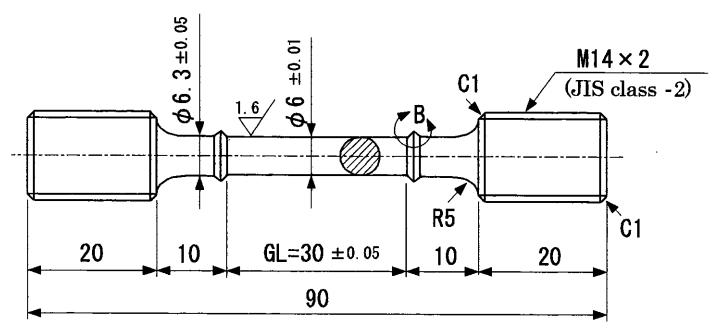
test temperature (℃)	Target range (℃)	JIS tolerance (℃)
600 max.	±2	±3
Over 600 up 800 incl.		±4
Over 800 up 1000 incl.		±5
1000 min.	±3	An agreement between persons concerned

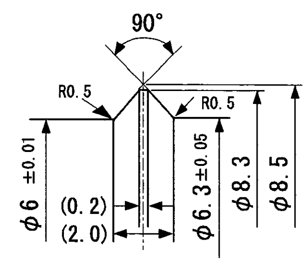




Details of a part

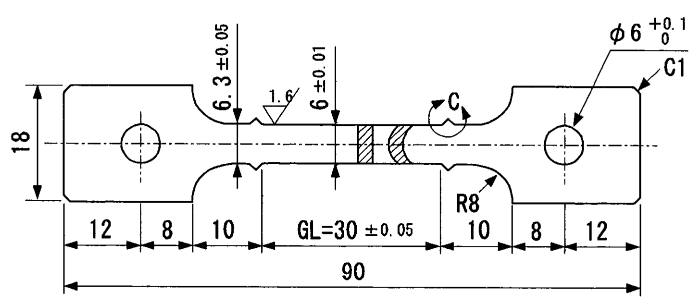
Test piece for tensile test (10φ)

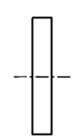




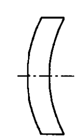
Details of b part

Test piece for tensile test(6φ)



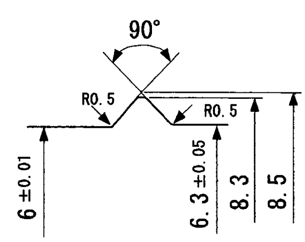


Flat form



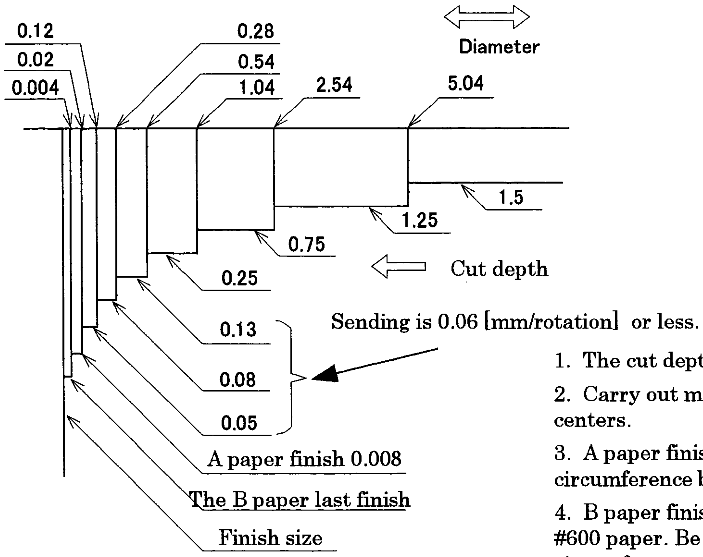
Arc section

Test piece for tensile test(Flat form ,Arc section)



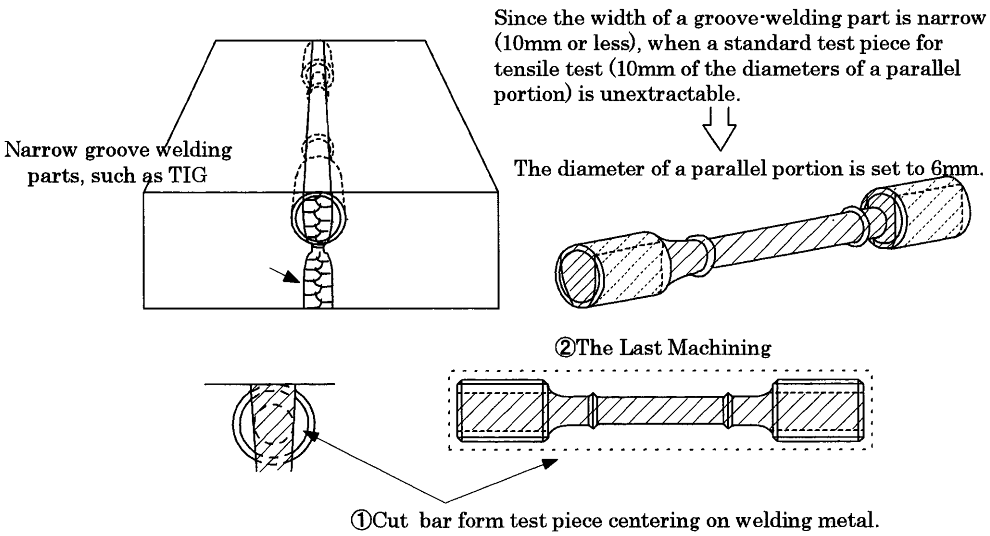
Details of c part

Fig. 2.1-1 Configuration of test piece for tensile test

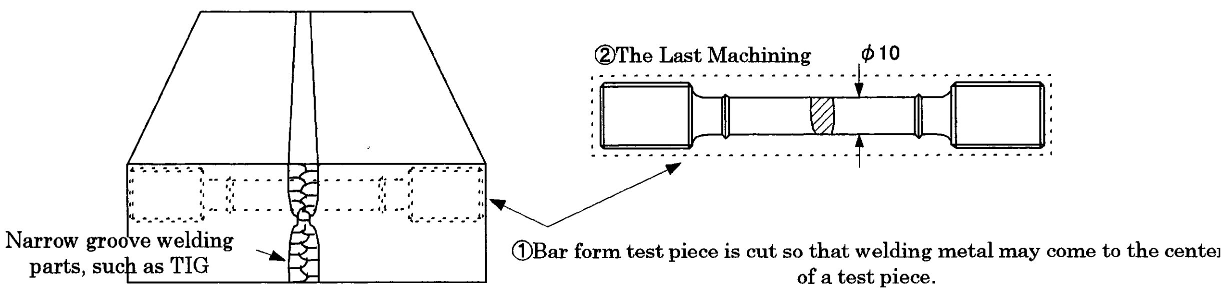


1. The cut depth by the lathe etc. shall follow the above figure.
2. Carry out machining finish from the cut depth 0.13 using both centers.
3. A paper finish finishes up by polishing in the direction of the circumference by #240 paper.
4. B paper finish finishes up by polishing in the direction of an axis by #600 paper. Be careful for there to be no crack of the direction of the circumference.

Fig. 2.1-2 The machining method of parallel portion of test piece



The example of a manufacture of the welding metal test piece for tensile test in narrow groove welding part



The example of a manufacture of the welding joint test piece for tensile test in a narrow groove-welding part

Fig. 2.1-3 Example of manufacture of special test piece for tensile test

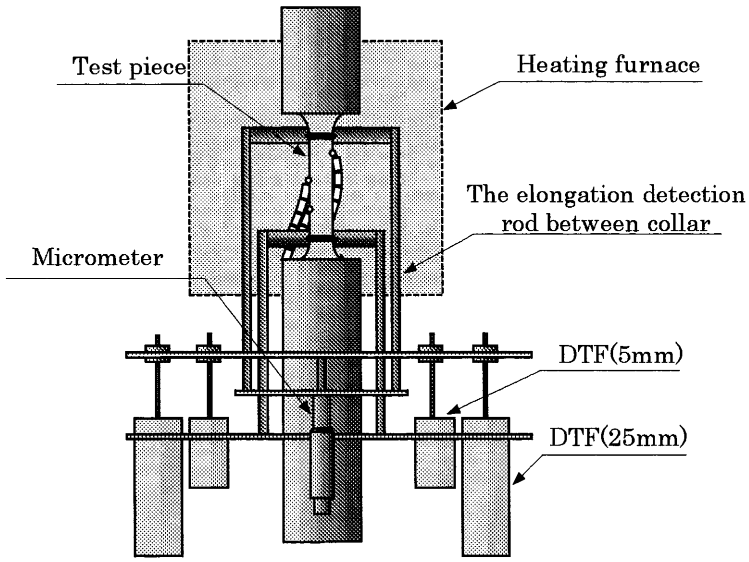


Fig. 2.1-4 Attachment figure of extensometer of arm shoulder type

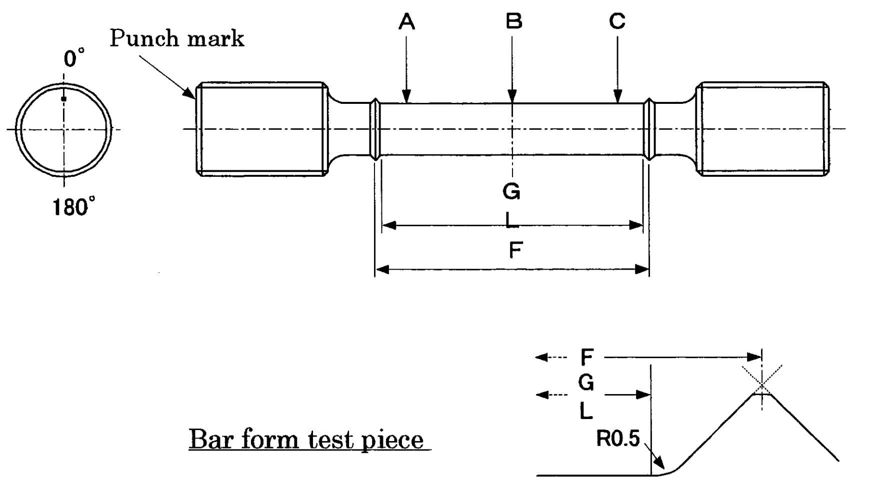
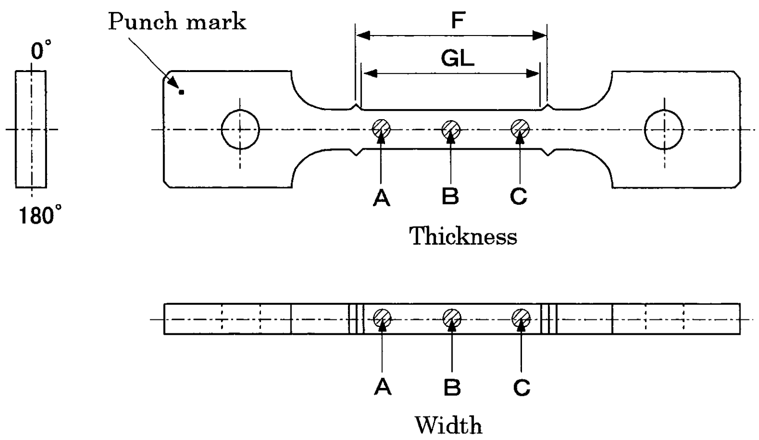
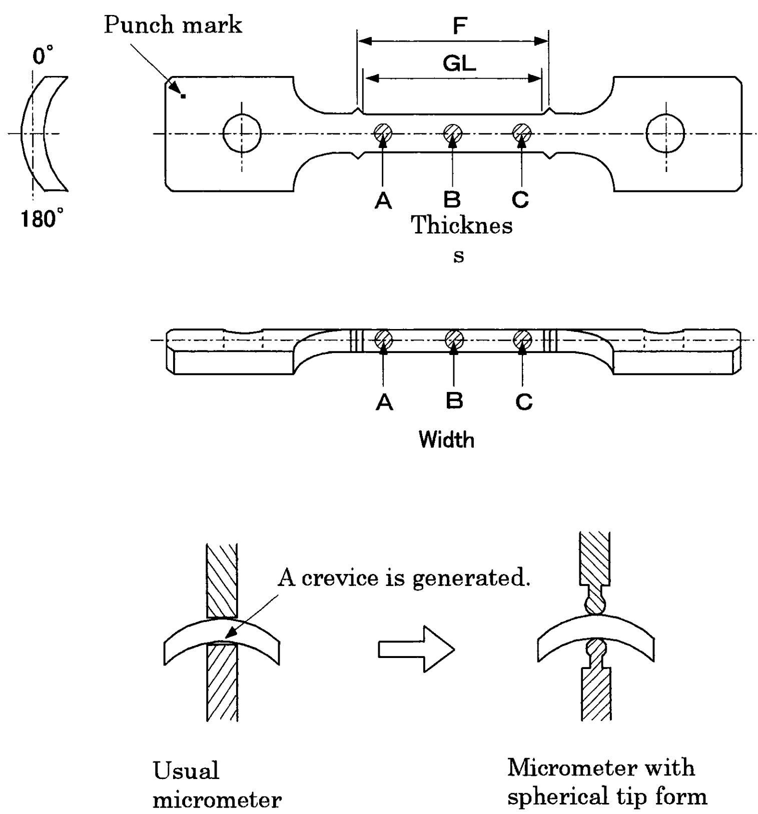


Fig. 2.1-5 Size measurement part of test piece for tensile test (1/2)



Flat form test piece



Arc section test piece

Fig. 2.1-5 Size measurement part of test piece for tensile test (2/2)

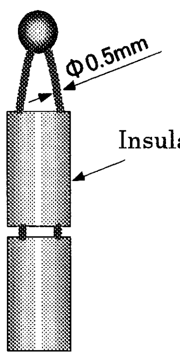


Fig. 2.1-6 Form of thermocouple tip part

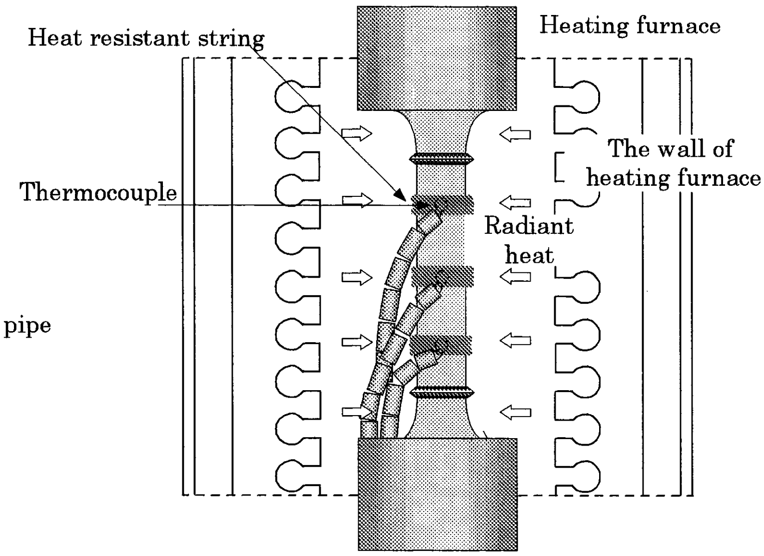


Fig. 2.1-7 Prevention of measurement error by radiant heat

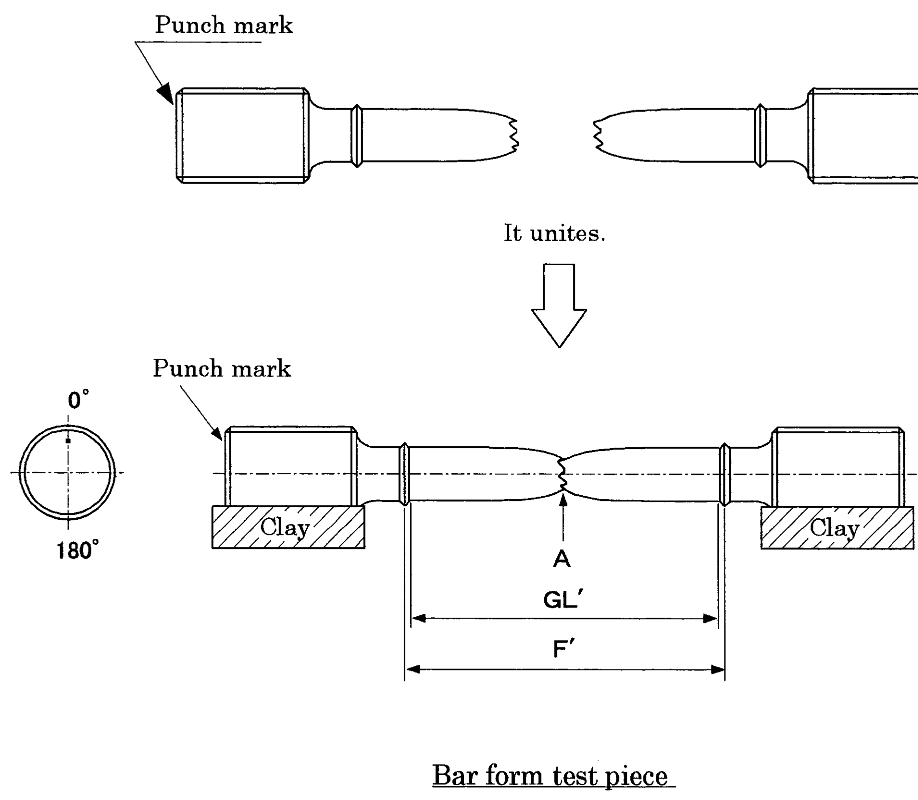
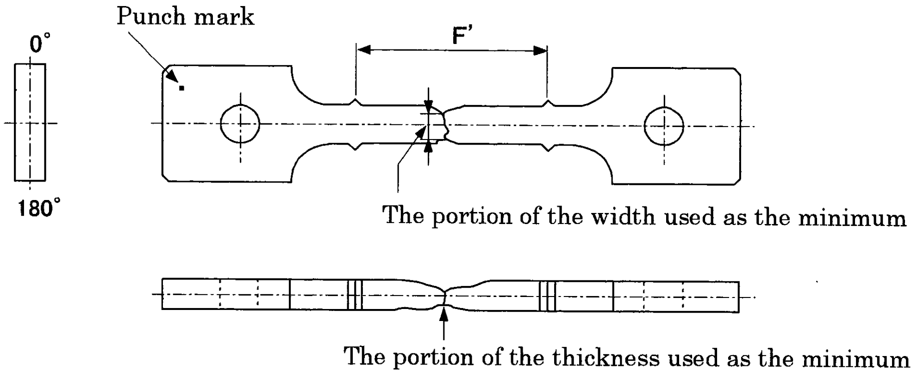
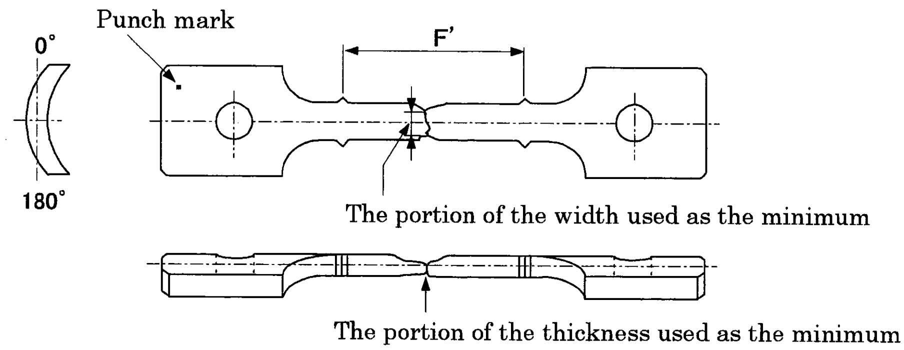


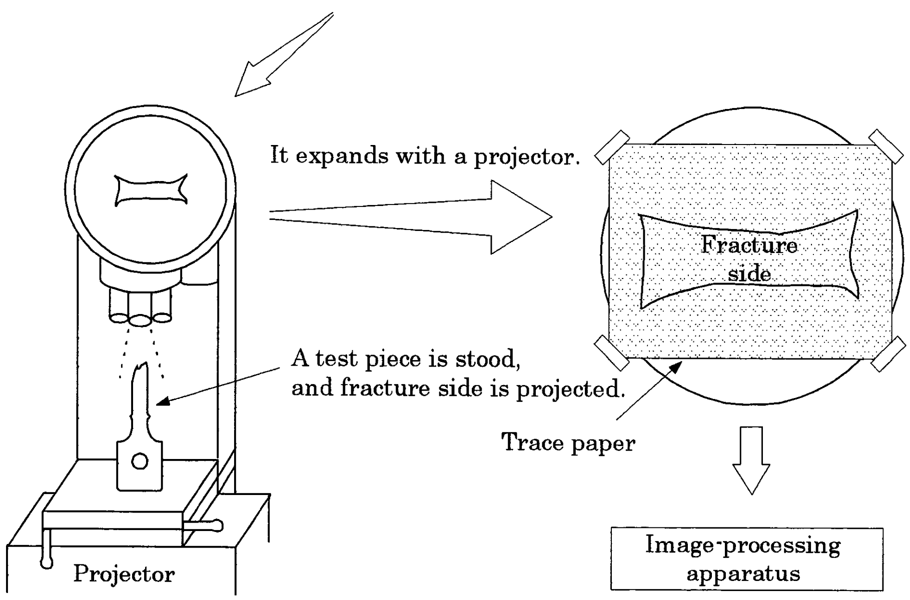
Fig. 2.1-8 Size measurement part after fracture (1/2)



Flat form test piece

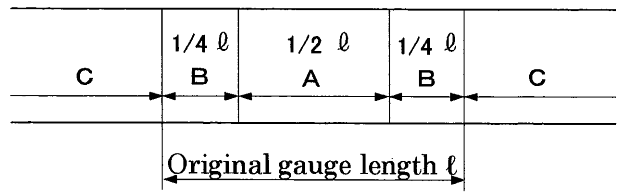


Arc section test piece

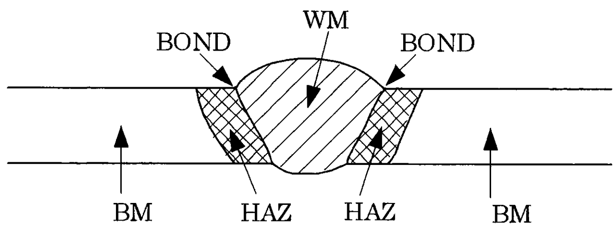


Special case

Fig. 2.1-8 Size measurement part after fracture (2/2)



Base material and Welding metal test piece



Welding joint test piece

Fig. 2.1-9 Indentification of location of fracture

2.2 Creep test (including creep rupture test)

2.2.1 Range

The rules described in this chapter shall apply to the creep test and the creep rupture test for FBR metallic materials

2.2.2 Definition of terms

Table 2.2-1 shows the definition of terms used in this test.

For unit notation, the International System of Units (SI) is used. However, for tests in progress that began before this procedure was prepared, may be converted and use conventional units (kg, kg/mm^2) for load and stress .

2.2.3 Test pieces

Test pieces used for this test shall generally comply with JIS Z 2271.

The gauge length (GL) shall be the distance between the inner ends of the collars.

Test materials include sheets, forgings, pipes, bars, etc, which have a uniform metal structure for fast reactor structural materials, as well as welded metals and joint materials.

(1) Test piece shape

As shown in Figure 2.2-1, the test piece shall generally be of round cross section, and the standard test piece shall be a solid round-bar shape with collars. The diameter of the parallel portion shall generally be 10 ϕ , but 6 ϕ , 8 ϕ or 12 ϕ diameters may be used. The length of the test piece parallel portion shall be 5D (D: diameter of the parallel portion), and this will be the gauge length.

Also, if the test piece of circular cross section cannot be obtained, a sheet test piece or arc section test piece prepared by machining asheet test piece or pipe (heat exchanger pipe) in the axial direction can be used.

Using test pieces of shapes and dimensions other than the standard test pieces shall be discussed and determined separately.

(2) Sampling positions

Same as Section 2.1 Tensile Test.

(3) Preparation method

Same as Section 2.1 Tensile Test.

(4) Preparation of special test pieces

Same as Section 2.1 Tensile Test.

2.2.4 Testing apparatus

Testing apparatus for this test must comply with JIS Z 2271.

Our group is equipped with a 3 ton, 1.5 ton, and 0.75 ton capacity Vertical Single Lever Loading Systems, and a 5 ton capacity Vertical Double Lever Loading System, and the system to be used depends on the purpose of the test.

Testing apparatus consists of a main test unit, an instrument for measuring elongation, a heating device, and a recording device. Specifications of the testing apparatus installed in our group are shown in Appendix2.2-1, and its diagram is shown in Appendix2.2-2.

(1) Main test unit

The main test unit shall consists of a main frame that has enough rigidity against external force, and a loading instrument whose structure core matches the direction load that is applied during the test. Also, accuracy of load shall be ±0.5%of 5 % to 100% of the load carrying capacity.

(2) Test piece grip (chuck)

The grip shall be shaped to ensure the core of a test piece, and shall be constructed so that forces other than the tensile force are not applied.

For round-bar type test pieces a screw-type grip is ideal, while for sheet and arc section test pieces, a pin grip is preferred. The materials of the grip shall be heat resistant alloys that will not weaken or be baked within the test temperature range and can withstand the tensile load.

Appendix2.2-3 shows an outline of a test piece grip.

(3) Instrument for measuring elongation

The instrument to be used to measure elongation of the test piece in axial direction shall conform to JIS B 7741 grade 1 or higher.

Elongation between gauge marks of the test piece will be measured by instruments such as the arm shoulder type extensometer (refer to Figure 2.2-2).

(4) Heating device

A heating device is used to apply heat to the test piece depending on the purpose of the test until the temperature reaches the test temperature. As a heating device, the electric fire heating furnace system is recommended. Thermocouples for detecting temperature shall comply with JIS C 1602, and R thermocouple with 0.5 ϕ diameter (JIS class – 2) shall generally be used. In addition, the PID adjustment system shall be used to control temperature.

(5) Recording device

To measure elongation and temperature, analog recorders or online data collection systems shall be used.

① Recorder

An analog recorder shall be used to record elongation between gauge marks and changes in temperature over time.

② Online data collection system

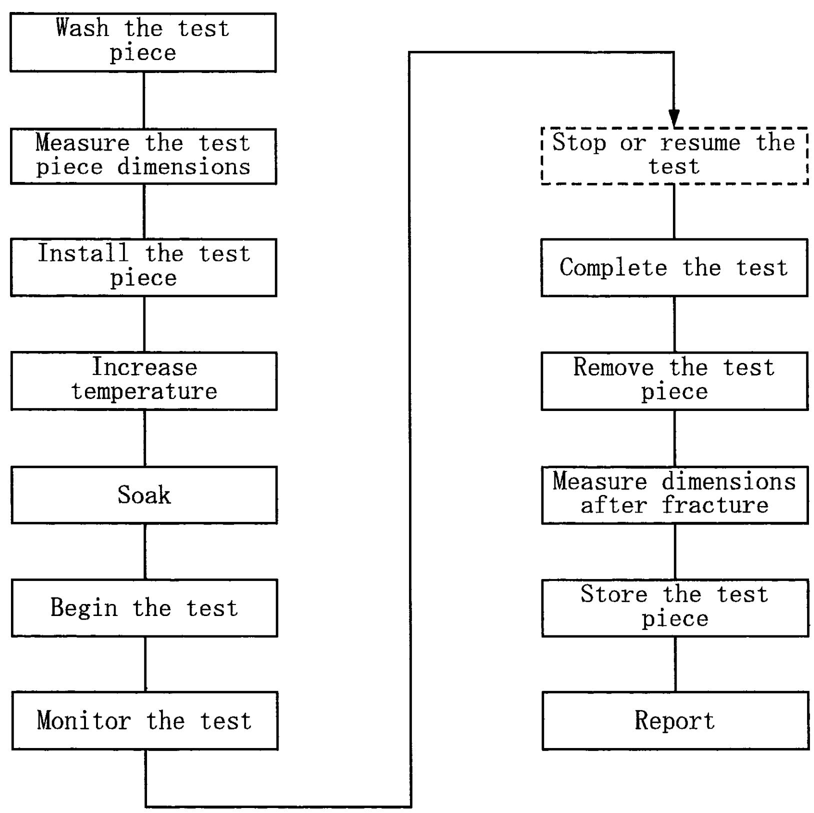
This system is used to sample temperature and elongation data every few seconds, which are outputted from the test unit, and to monitor its operation.

Appendix 2.2-4 shows the configuration of an online data collection system.

2.2.5 Test methods

Test temperature, loading method and measurement method of elongation shall be in compliance with JIS Z 2271.

Standard test procedures for the creep test are shown below.



(1) Washing the test piece

Same as Section 2.1 Tensile Test

(2) Measuring the dimensions of the test piece

Same as Section 2.1 Tensile Test

(3) Installing the test piece

When installing the test piece, care should be taken to avoid applying torsion or bending load to the test piece.

(4) Heating method

Using the heat resistant cord, tie two thermocouples at both ends of the parallel portion of the test piece, and a third thermocouple at the center of the parallel portion of the test piece. Heat the test piece by an electric furnace, etc, and adjust the temperature at the three thermocouples to be within the target range shown in table 2.2-1. Details on the tip shape of thermocouples and prevention of measurement errors due to radiant heat will be the same as Section 2.1 Tensile Test.

Temperature shall be increased within 1 to 4 hours, and the soaking time to maintain thermal equilibrium of the test piece after reaching the specified temperature shall be 16 to 24 hours.

The thermocouples shall be replaced with new ones before 10 years of use if the test temperature is 550 degree or less, or before 1×10^4 hours if the test temperature is over 550 degree, in consideration of the relationship between temperature and hours of use causing deterioration of an R thermocouple [1]. Those thermocouples exceeding the specified hours of use shall be recast and reused.

(5) Loading method

The standard loading method shall be a gradual loading. After soaking, to confirm operation of the testing apparatus, put a plumb bob weighing less than 10% of the test load and hold it for a couple of minutes. Then, after applying and removing the load within the loading range to minimize the creep strain occurring during loading, the test load shall be applied as rapidly as possible. The start time of the test will be when loading is completed. Figure 2.2-3 shows the schematic diagram of the gradual loading method.

(6) Recording the creep test data

Creep strain and changes in temperature according to time shall be recorded by an analog recorder, etc.

Also, if an online data collection system is used, measurement intervals shown in table 2.2-3 are recommended to measure creep strain and temperature.

(7) Monitoring the test

A few minutes after the test has started, verify that temperature, elongation, etc appear normal. After that, periodic monitoring shall be performed until the test is completed.

(8) Stopping/Resuming the test

When the test is interrupted due to aberrance, remove the cause and resume the test. However, if any problems that may affect strength evaluation, such as significant change in elongation or temperature increase, are identified, the test shall be aborted.

If the test is to be interrupted (by shutting the power of the heating furnace off) due to electric power suspension, etc, keep the test piece loaded with the plumb bob during the interruption. Maintain the load condition when the test is to be resumed (by turning the power of the heating furnace ON). When the test piece temperature reaches the tolerance level of JIS, the test may be resumed.

Any interruption/resumption(s) of the test shall be reported in the test data records.

(9) Completing the test

The test is completed when the target test hours are met or when the test piece is fractured. The time from load completion until creep rupture occurs or the target test hours are reached, shall be the rupture time or the testing time. However, down time during the testing shall be subtracted.

(10) Compensating strain

As shown in Figure 2.2-4, behavioral data of the strain during the test may be caused by an earthquake, lever position adjustment, and extensometer adjustment, etc. For test data, strain shall be compensated.

Here, any records of compensation shall be recorded along with the data.

(11) Measuring dimensions after fracture

Same as Section 2.1 Tensile Test

(12) Storing the test piece

Same as Section 2.1 Tensile Test

(13) Determining the fracture location

Same as Section 2.1 Tensile Test

2.2.6 Report of test results

The following items shall be reported as creep test data. Routine datasheets and graphs are shown in Appendix2.2-5, 6 and 7.

(1) Name of material (type of steel, heat No)
(2) Quality and shape of the test piece (including the past records of the test piece)
(3) Detailed specifications of the testing apparatus
(4) Test conditions
  ① Test temperature
  ② Specified temperature if the test temperature varies from the range of tolerances.
  ③ Stress
  ④ Time of temperature increase
  ⑤ Soaking time
(5) Test method
(6) Test results
  ① Strain-time diagram
  ② Loading time, strain on load, Steady Creep Rate, Primary Creep Strain, Time to Secondary Creep and strain, and Time to Tertiary Creep and strain
  ③ Time to rupture
  ④ Elongation at rupture, reduction of area
  ⑤ Fracture location, etc
(7) Others, presence or absence of aberrance that occurred during testing

2.2.7 Adding the test results to the database

Same as Section 2.1 Tensile Test

2.2.8 Normative references

① JIS B 0031-1994 JIS Technical drawings - Methods to indicate surface texture on drawings
② JIS B 0601-1994 JIS Surface roughness - definitions and designations
③ JIS B 7741-1999 JIS Verification of extensometers used in uni-axial testing
④ JIS C 1602-1995 JIS Thermocouples
⑤ JIS G 0202-1987 JIS Glossary of terms used in iron and steel (testing)
⑥ JIS Z 2271-1999 JIS Creep and creep rupture test methods for metallic materials
⑦ JIS Z 8401-1999 JIS Standards for rounding off of numerical values

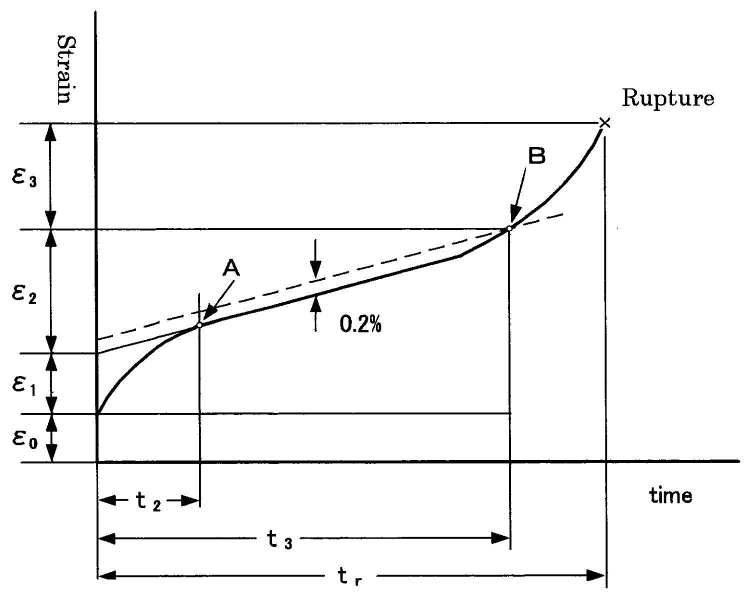
※ For normative references without year of publication, the most recent edition applies.

Table 2.2-1 Definition of terms regarding creep test and creep rupture test

No.	Terms	Standard symbols (unit)	Descriptions
1	Test Temperature (specified temperature)	T (℃)	Average temperature during the test
2	Stress	σ (N/mm^2)	Test load P divided by the original cross-sectional area (A_0) of the test piece. $\sigma = P/A_0$
3	Strain on Load	ε_0 (%)	Strain when the test load is completed after reaching the test temperature. (Elastic strain) + (Non-elastic strain)
4	Total Strain	ε_t (%)	(Strain on Load) + (Creep strain)
5	Creep Strain	ε_C (%)	(Total strain) − (Strain on Load)
6	Primary Creep Strain	ε_1 (%)	Total strain at the intersection of the vertical axis and the straight line portion of the creep curve extending over time 0, minus Strain on Load ε_0(Refer to attached figure 2.21).
7	Secondary Creep Strain	ε_2 (%)	Total strain at the starting point of the Tertiary Creep Strain, minus Strain on Load, minus Primary Creep Strain (Refer to attached figure 2.2-1).
8	Tertiary Creep Strain	ε_3 (%)	Strain obtained by subtracting Strain on Load, Primary Creep Strain, and Secondary Creep Strain from Fracture elongation (strain)(Refer to attached figure 2.2-1).
9	Time to Secondary Creep	t_2 (hr)	Time from when loading is completed to the time period A when the strain rate starts to level out (refer to attached figure 2.2-1).
10	Time to Tertiary Creep	t_3 (hr)	Time from when loading is complete to the point in time when the strain rate starts to accelerate. This specifies the time at intersection B (refer to attached figure 2.2-1). First, the straight line portion of the creep curve is extended to time 0. Then, the strain of 0.2% of the gauge length is added to the strain at the intersection of this line and the vertical axis, and the straight line is extended from this point parallel to the straight line part of the creep curve until it intersects with B.
11	Steady(Secondary)Creep Rate	ε_s (%/hr)	Strain rate at the straight line where the slope of the creep curve levels out
12	Rupture Time	t_r (hr)	Time from when loading is completed to the creep rupture.

Table 2.2-1 (continued) Definition of terms for the creep test and creep rupture test

No.	Terms	Standard symbols (unit)	Descriptions
1 3	Fracture Elongation	δ (%)	The gauge length obtained by butting after rupture ℓ, minus the gauge length ℓ_0 before starting the test, divided by ℓ_0 $\delta = (\ell - \ell_0)/\ell_0 \times 100$
1 4	Reduction of Area	ϕ (%)	The original cross sectional area of the test piece parallel portion A_0 minus the minimum cross-sectional area A of the fractured portion, divided by A_0 $\phi = (A_0 - A)/A_0 \times 100$
1 5	Fracture Location		In accordance with the regulation in Section2.1 Tensile Test
1 6	Gauge Length	ℓ_0 (mm)	The length between reference marks used to calculate the strain. When the test piece has collars, the gauge length shall be the length between inner ends of collars as described in detail in Figure 2.2-1.



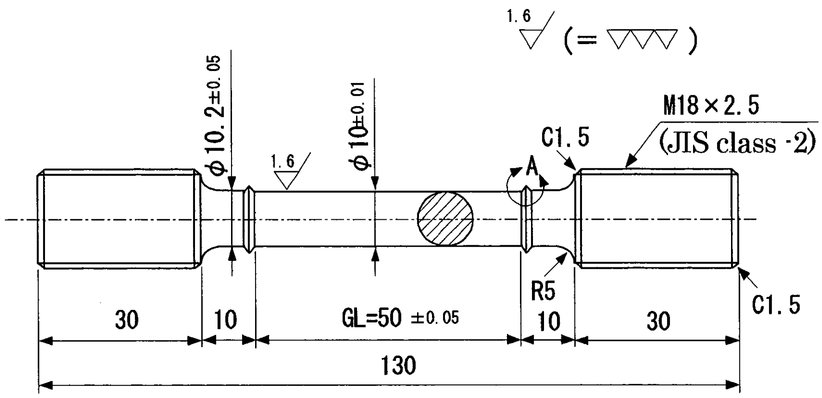
Reference Figure 2.2-1 Simulation of a creep curve

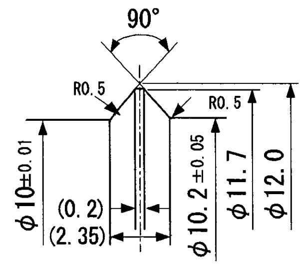
Table 2.2-2 Target range of test temperature

Test temperature (℃)	Target range (℃)	JIS tolerances (℃)
900 max.	±2	±3
Over 900 up 1000 incl.		±4

Table 2.2-3 Measurement interval of creep data (recommendation value)

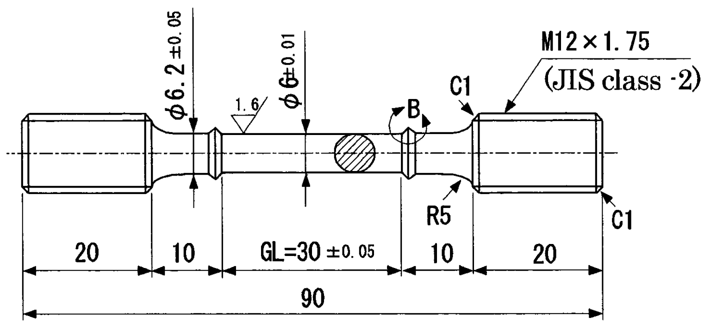
Start time (hr)	End time (hr)	Measurement interval (hr)	Number of data	Accumulation number of data
0	0.2	0.01	20	20
0.2	1	0.05	16	36
1	2	0.1	10	46
2	10	0.5	16	62
10	100	2.0	45	107
100	1000	10.0	90	197
1000	5000	20.0	200	397
5000	10000	50.0	100	497
10000	200000	100.0	1900	2397

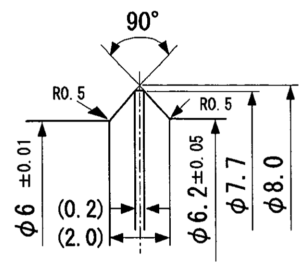




Details of A part

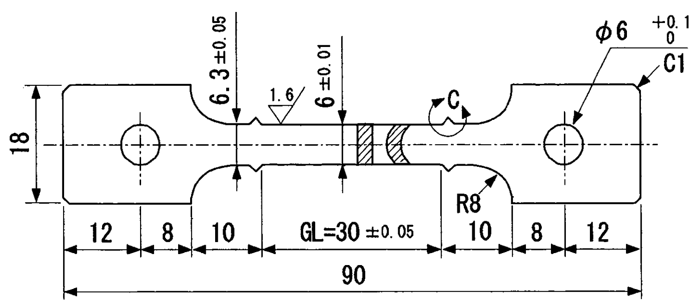
Test piece of creep test (10φ)

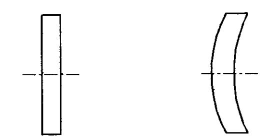




Details of B part

Test piece of creep test (6φ)

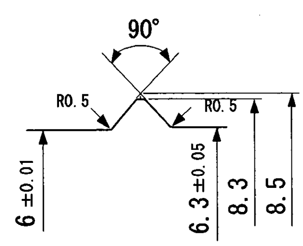




Flat form

Arc section

Test piece of creep test (Flat form,Arc section)



Details of C part

Fig. 2.2-1 Configuration of test piece for creep test in air

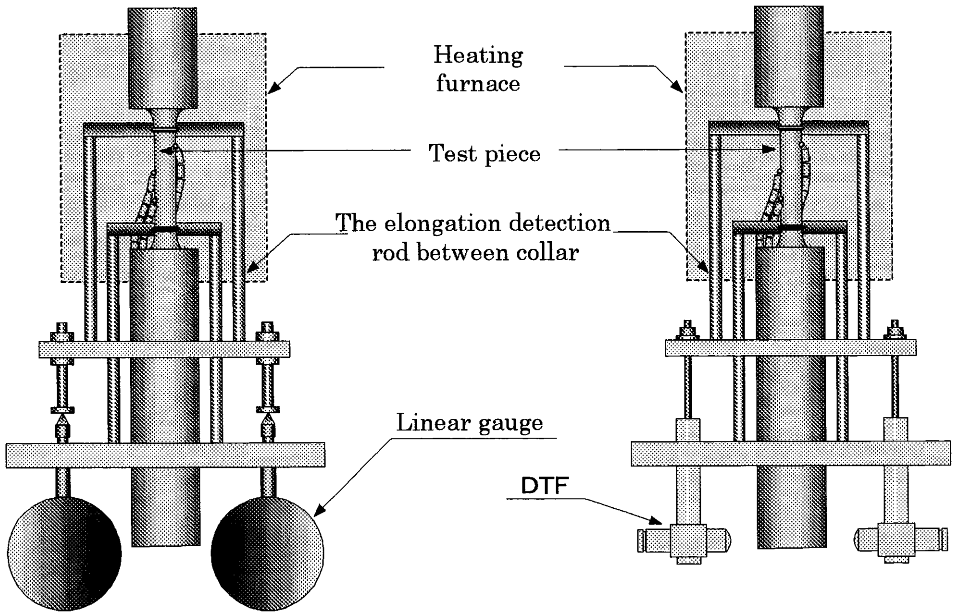


Fig. 2.2-2 Attachment figure of extensometer of arm shoulder type

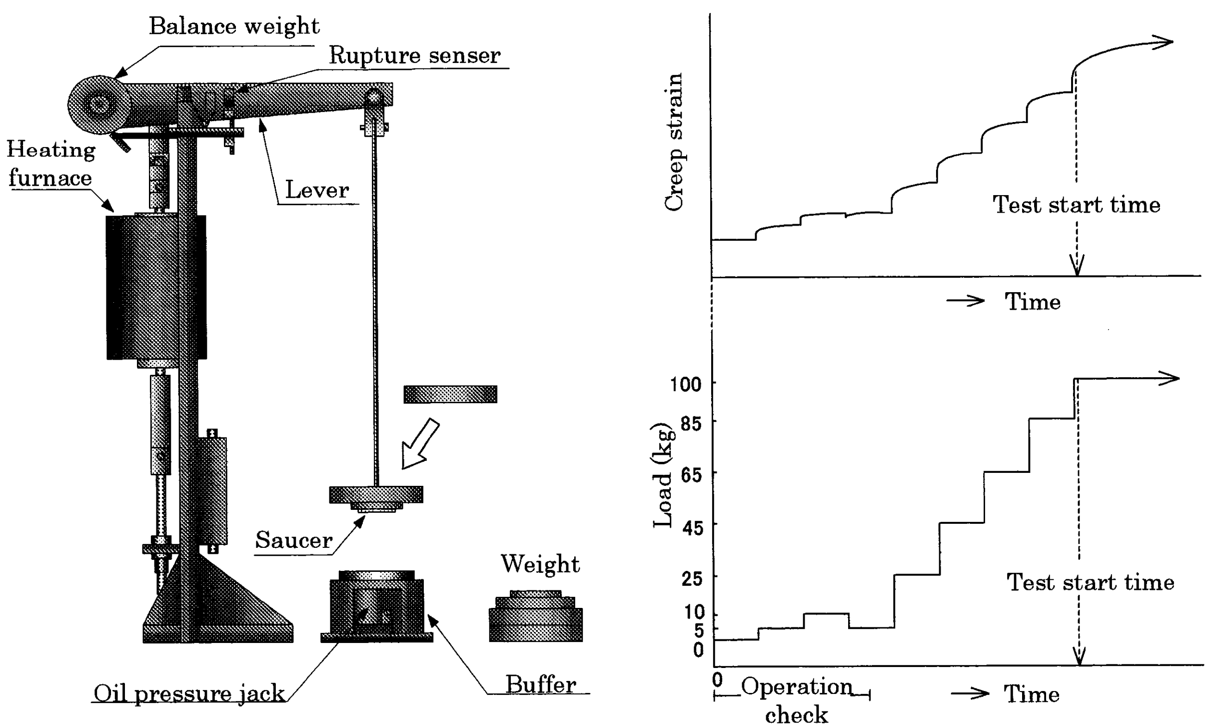


Fig. 2.2-3 Stage load method

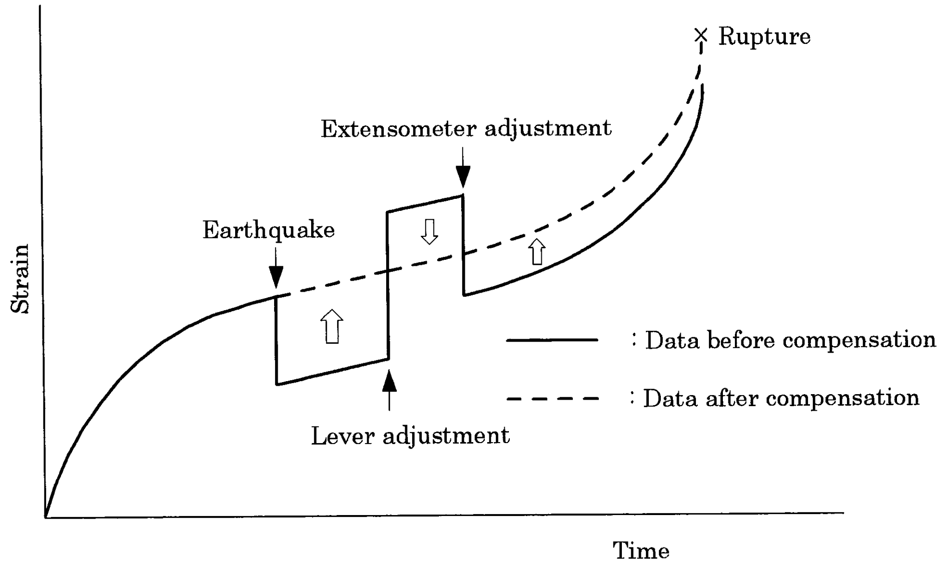


Fig. 2.2-4 Strain compensation processing of creep curve

2.3 Relaxation Test

2.3.1 Range

The standards described in this chapter shall apply to the relaxation test for FBR metallic materials.

2.3.2 Definition of terms

Table 2.3-1 shows the definition of terms used in this test.

As for unit notation, the International System of Units (SI) is used.

2.3.3 Test pieces

Test materials shall include sheets, forgings, pipes, bars, etc, that have a uniform metal structure for fast reactor structural materials, as well as welded metals and joint materials.

(1) Test piece shape

As shown in Figure 2.3-1, the test piece shall be a solid round-bar shape with collars. The diameter of the parallel portion shall generally be 10 ϕ, but 6 ϕ, 8 ϕ or 12 ϕ diameters may be used. The gauge length shall, as a rule, be 100 mm in either case.

Since the strain controlled in the relaxation test is small, $\pm 0.5\,\mu$m, and if the gauge length is short and the total strain value is small, the variation range of the total strain caused by sensitivity of elongation detection will be large. Therefore, the gauge length shall generally be 100 mm for lever type testing apparatus.

Furthermore, using test pieces of shapes and dimensions other than that of the standard test pieces shall be discussed and determined separately .

(2) Sampling positions

Same as Section 2.1 Tensile Test

(3) Preparation method

Same as Section 2.1 Tensile Test

(4) Preparation of special test pieces

Same as Section 2.1 Tensile Test

2.3.4 Testing apparatus

Testing apparatus for this test must comply with JIS Z 2276.

A lever-type self-balancing testing device is recommended as a relaxation testing device. Load control shall be carried out by plumb bob or relaxation weight, and the load is adjusted by changing each weight.

The testing apparatus shall consist of a main test unit, an instrument for measuring elongation, a heating device, and a recording device. Specifications of testing apparatus installed in our group are shown in Appendix2.3-1 and its diagram is shown in Appendix2.3-2.

For a few hundred hours of testing, a hydraulic servo type fatigue testing machine can be used as well, although caution is required as the shape of test piece and others will vary from JIS standards.

(1) Main test unit

The main test unit shall be constructed so that load direction during the test matches the center, and high accuracy is maintained, and shall consist of a loading device that exerts load onto the test piece, relaxation weight portion attached to the load lever, chuck gap, and lower pull rod adjustment portion that adjusts the horizontal position of the lever. Also, load accuracy shall be within ±0.5%.

(2) Test piece grip (chuck)

The grip shall be shaped to ensure the center of a test piece, and a screw-type is recommended. The materials of the grip shall be heat resistant alloys that will not weaken or be baked within the test temperature range and can withstand the tensile load.

Appendix2.3-3 shows an outline of a test piece grip.

(3) Instrument for measuring elongation

Instruments such as the arm shoulder type extensometer (digital linear gauge) shall be used to measure elongation between gauge marks of the test piece. To stabilize the strain during the relaxation test, deviation of elongation detected by the extensometer and the specified strain will be transmitted to the loading instrument. Figure 2.3-2 shows an outline of the arm shoulder type extensometer.

(4) Heating device

A heating device is used to apply heat to the test piece depending on the purpose of the test, until the temperature reaches the test temperature. As a heating device, the electric fire heating furnace system is recommended. Thermocouples for detecting temperature shall comply with JIS C 1602, and R thermocouple with 0.5ϕ diameter (JIS class – 2) shall generally be used. In addition, the PID adjustment system shall be used to control temperature.

(5) Recording device

To measure stress, strain, deviation and temperature, a recorder or an online data collection system shall be used.

① Recorder

An X – TY recorder shall be used to record stress, strain, and deviation, and a temperature recorder shall be used to record changes in temperature over time.

② Online data collection system

This system is used to sample stress-strain in chronological order and to monitor the operation of the testing machine.

Appendix 2.3-4 shows the connection outline of the online data collection monitoring system.

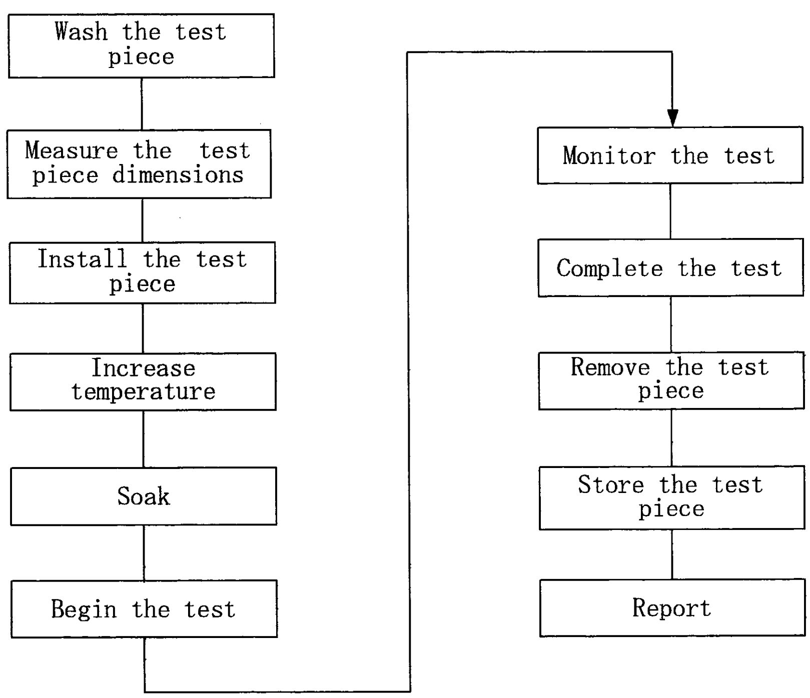
(6) Testing apparatus installation environment

Testing apparatus and other various detecting devices must be kept in a stable environment during the testing period in order to obtain reliable data and quality improvement. As the control strain in relaxation test is a very small strain of ±0.5 μm, it can easily be affected by the ambient temperature around the testing apparatus or surrounding atmosphere. Therefore, adjusting room temperature variation to within ±2℃, and covering the surrounding area of the testing apparatus with twofold windshield cover to maintain temperature variation of the testing apparatus within ± 0.5 ℃, is recommended. As shown in Figure 2.3-3, these preparations are necessary to aviod changes in load due to room temperature variations caused by air conditioning, and to obtain accurate relaxation behavioral data.

2.3.5 Test methods

Test temperature, loading method and measurement method for elongation and load shall conform to JIS Z 2276.

Standard test procedures for relaxation test are shown below.



(1) Washing the test piece

Same as Section 2.1 Tensile Test

(2) Measuring the dimensions of the test piece

Same as Section 2.1 Tensile Test

(3) Installing the test piece

When installing the test piece, care should be taken to avoid applying torsion or bending load to the test piece.

(4) Heating method

Same as Section 2.2 Creep Test

(5) Loading method

After soaking, put a plumb bob weighing less than 10% of the test load in and remove the entire load or part of the load to verify testing apparatus operation. Then move the relaxation weight as rapidly as possible until the strain value reaches the set value to start the test. The strain control accuracy during the test shall be within ±1.5%.

As shown in Figure 2.3-4, it is useful to hold the load control (if the relaxation weight is stopped) for very short time before the set strain value is reached, in case the moving speed of relaxation weight of the testing machine cannot follow the sudden decrease in stress caused immediately after starting the test. The holding time of the load control shall be 30 seconds at maximum.

(6) Recording the relaxation test data

After finishing loading with a plumb bob, record the starting time of the relaxation test, strain and stress.

For load control holding test, record the holding time, strain and stress.

After starting the relaxation test, continuously record the strain, stress and changes according to time for the entire testing period.

If equipped with an online data collection system, the recommended data (stress, strain) sampling times are 0, 0.001, 0.002, 0.003, 0.004, 0.006, 0.008, 0.01, 0.02, 0.03, 0.04, 0.06, 0.08, 0.1・・・・(hr).

(7) Monitoring the test

Periodic monitoring shall be performed until the test is completed. Resumption of the relaxation test due to test interruption will not generally be carried out.

(8) Completing the test

The time the test is completed shall be the completion of the test.

(9) Storing the test piece
Same as Section 2.1 Tensile Test

2.3.6 Reporting the test results

The following items shall be reported as the relaxation test data. Typical datasheets and graphs are shown in Appendix2.3-5 and 6.

(1) Name of material (type of steel, heat No.)
(2) Quality and shape of the test piece (including the past records of the test piece)
(3) Detailed specifications of the testing apparatus
(4) Test conditions
 ① Test temperature
 ② Total strain
 ③ Time for increasing temperature, soaking time
 ④ Loading rate
 ⑤ Time fromwhen loading is completed to when measuring relaxation starts
 ⑥ Load control holding time
(5) Test method
(6) Test results
 ① Stress on load, residual stress
 ② Relaxation diagram or measurement values with which an accurate relaxation diagram can be drawn, etc.
(7) Others, presence or absence of aberrance that occurred during the test

2.3.7 Adding the test results to the database

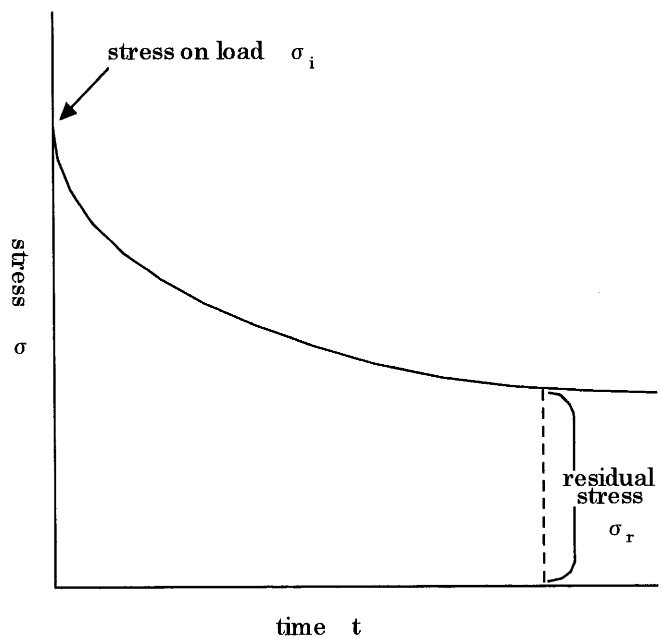
Same as Section 2.1 Tensile Test

2.3.8 Normative references

① JIS B 0031-1994 JIS Technical drawings – Methods to indicate surface texture on drawings
② JIS B 0601-1994 JIS Surface roughness - definitions and designations
③ JIS C 1602-1995 JIS Thermocouples
④ JIS Z 2276-1975 JIS Tensile stress relaxation test methods for metallic material
 ※ For normative references without year of publication, the most recent edition applies.

Table 2.3-1 Definition of terms for relaxation test

No.	Terms	Standard symbols (unit)	Descriptions
1	Relaxation	—	Stress relaxation (decrease of stress) is the phenomena when the stress of a test piece decreases over time under stable total strain conditions.
2	Gauge Length	ℓ_0 (mm)	Area of the test piece used to measure elongation (refer to Figure 2.3-1)
3	Nominal Stress	σ (N/mm^2)	The load P divided by the original cross-sectional area of the test piece. $\sigma = P / A_0$
4	Stress on Load	σi (N/mm^2)	The maximum stress applied during the initial loading. Also referred to as Initial Stress. (refer to attached figure 2.3-1)
5	Residual Stress	σr (N/mm^2)	The load stress on the test piece at any time during the test (refer to attached figure 2.3-1).
6	Total Strain	εt (%)	The ratio of the elongation at the test temperature to the gauge length measured at an ordinary temperature



Reference Figure 2.3-1 Simulation of a relaxation curve

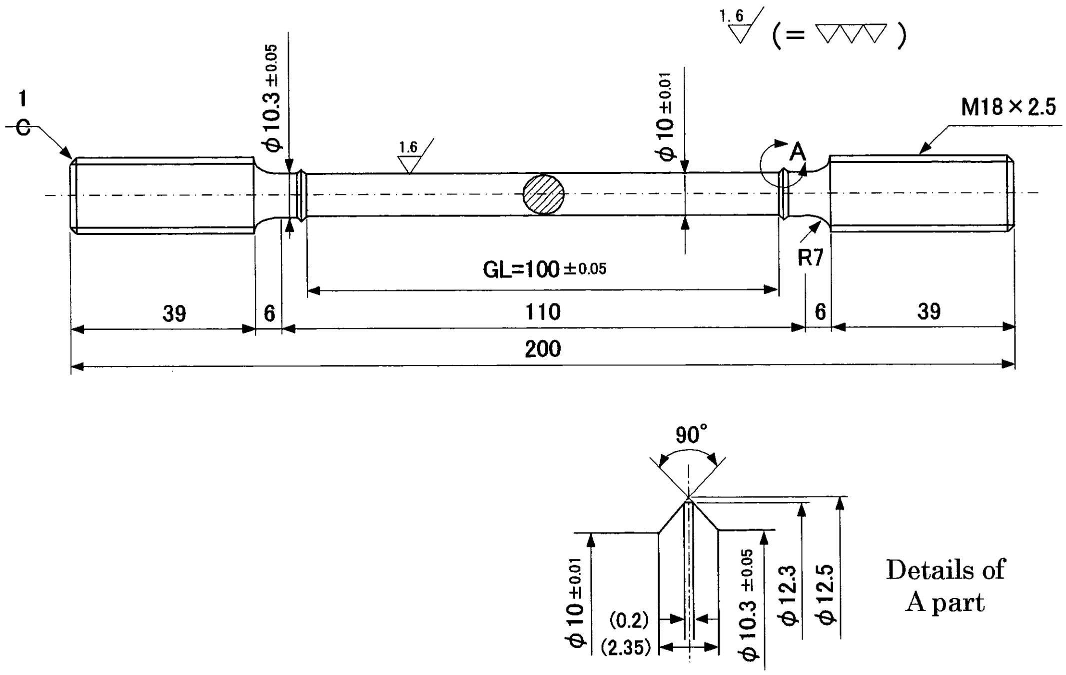


Fig. 2.3-1 Configuration of test piece for relaxation test

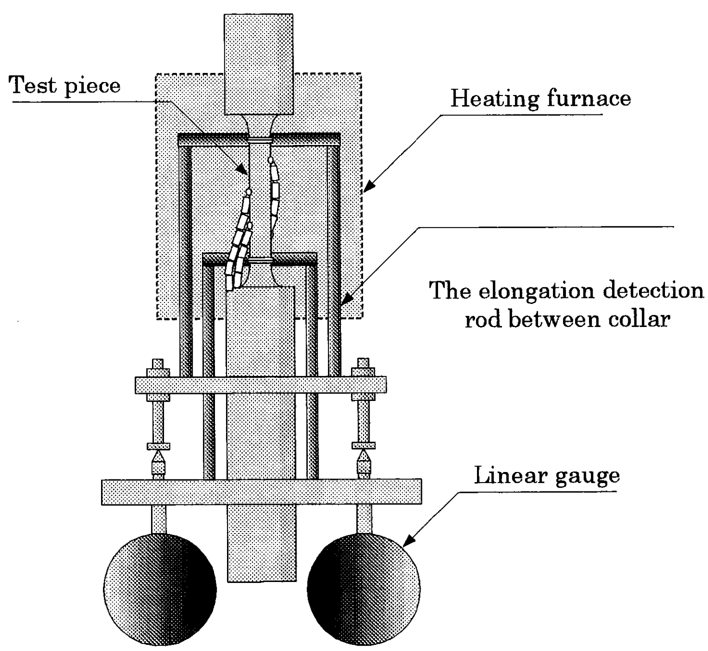


Fig. 2.3-2 Attachment figure of extensmeter of arm shoulder type

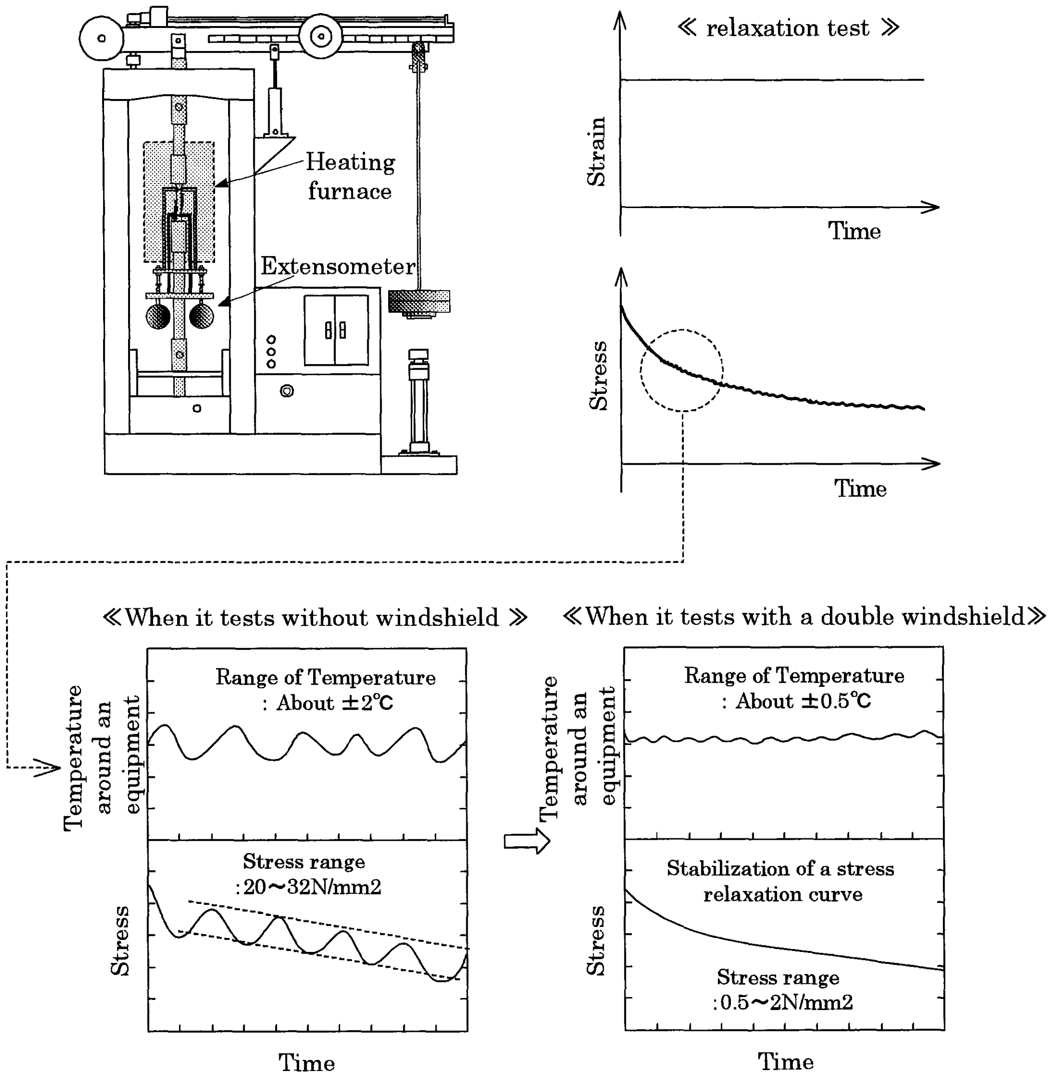
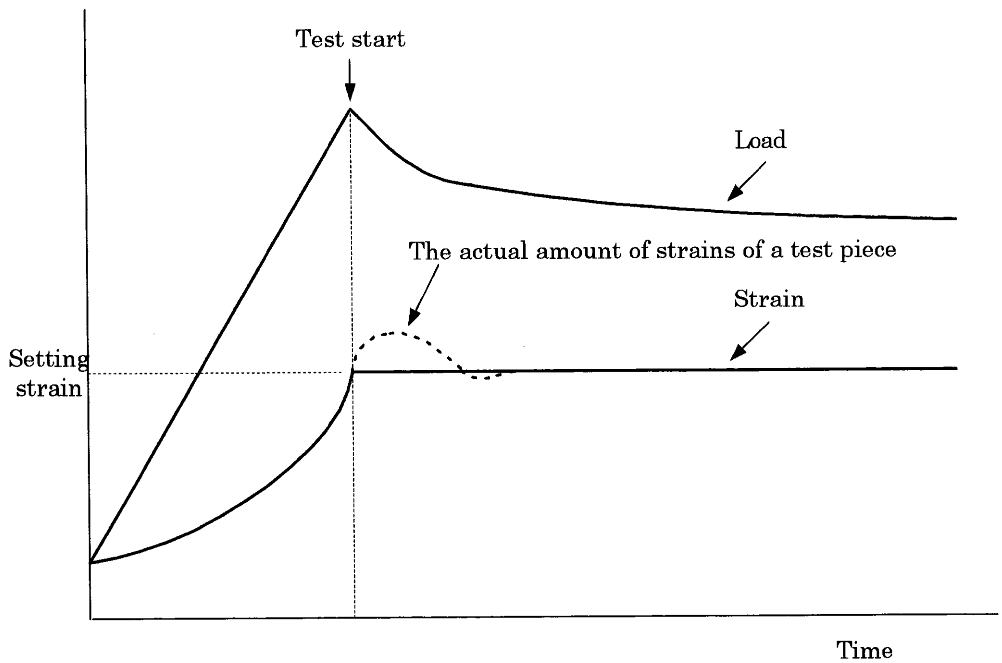
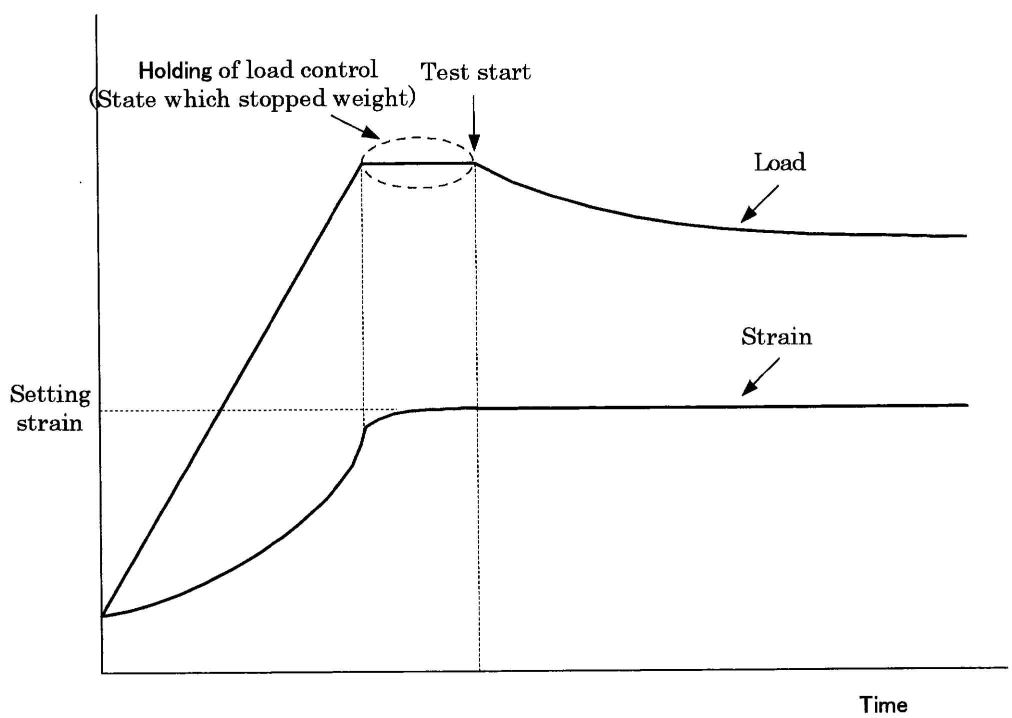


Fig. 2.3-3 Example of improvement of testing accuracy by double windshield



When it tests without holding of load control



When it tests with holding of load control

Fig. 2.3-4 Comparison of relaxation behavior

2.4 Low cycle Fatigue Test

2.4.1 Range

This procedure can be applied to low cycle fatigue tests and creep-fatigue tests of metallic materials used for fast breeder reactors in air and sodium environment.

2.4.2 Definition of terms

Definition of term is shown in Table 2.4-1.

The international units (SI units) are employed according to Japanese Industrial Standard (JIS).

2.4.3 Test pieces

Test pieces should be prepared referring to JIS Z 2279.

Materials covered in this manual are plates, forgings, tube, and pipe as well as their weld metal and welded joints for the structures of fast breeder reactors, which have uniform metallurgical structure.

(1) Configuration of test pieces

For in-air tests, the standard configuration of a test piece is round bar as shown in Fig. 2.4-1 (Diameter of the parallel portion is 6mm or 10mm). To avoid strain concentration, no projection is made in a parallel portion for the attachment of an extensometer. Two kinds of configurations with different types of grips such as a "button type" and a "screw type" are shown in Fig. 2.4-1.

For in sodium the standard configuration of a test piece is round bar as shown in Fig. 2.4-2 (Diameter of the parallel portion is 10mm). And the spacer for pouring sodium, the spacer for measuring the sodium flow velocity, the bellows for making expansion and contraction absorb, the structure which welded these is desirable. In addition, in order to evaluate the sodium environmental effect, a test-piece simple substance (state which does not attach a bellows, a spacer, etc.) can compare with test in air.

Configurations other than the standard type can also be used if justified.

(2) Location of cutting out a test piece

See "2.1 Tensile Test"

(3) Machining of a test piece

See "2.1 Tensile Test"

(4) Manufacturing special test pieces

When a piece of material available is too small to cut out a whole test piece, it is possible to make a parallel portion and grips separately and then weld them as shown in Fig. 2.4-3. In this case, a welding procedure must be carefully chosen sot that the effects of thermal strain on the parallel portion be as little as possible: electro-beam welding or Tungsten Inert Gas welding are recommended. Also, welded joints should be located as far as possible from the parallel portion. As regards to weld metal test pieces and welded joint test pieces, it is recommended to use the same procedure as that for special tensile test pieces (2.1).

2.4.4 Testing apparatus

Test apparatus used for fatigue tests should be in accordance with JIS Z 2279.

Push-pull fatigue test machine should be controlled by a closed loop electro-hydro servo system, or an electro servo motor system with a ecentric cum system or a ball screw system, designed to minimize backrush. It is necessary that load and strain can be controlled.

The closed loop electro-hydro servo system, which is widely used, is mainly employed for elevated temperature low cycle fatigue tests and relatively short-term creep-fatigue tests. This type of machine has good response and allows large load and high strain rate. Machines with electro servo motor system are used for long-term low strain rate fatigue tests or long-term creep-fatigue tests.

These fatigue test machines are composed of loading apparatus, strain measurement apparatus, heating apparatus, load measurement apparatus, measurement and controlling apparatus, etc. An example of the specifications of a machine is shown in Appendix 2.4-1. An illustration of the system is shown in Appendix 2.4-2 and Appendix 3.

(1) Loading apparatus

Loading apparatus (actuator) of an electro-hydro servo controlled machine is composed of servo valves that control the flow of oil, a rod, and a displacement detector that measures the movement of the rod, etc. A test piece is protected from abnormal loads by the drop of oil pressure and switch of control (strain control to load control).

In the case of machines with an electro servo motor system, an eccentric cum and a ball screw are used for controlling a test piece. Unloading is done by the release of crutch in the case of an eccentric cum system, and by the release of hydro pressure lock in the case of a ball screw system.

(2) Chuck

The configuration of chuck must be such that it reserves the center of axis of the test piece and prevents buckling of a test piece. Also, the configuration must be such that excessive torsion moment should not be imposed on the test piece when mounting a test piece. Chuck must be capable of imposing push-pull loading without loosening or baking.

(3) Strain measurement apparatus

Strain measurement apparatus should have an static accuracy of ±1.0% of the full scale of each range.

Axial strain measurement apparatus is described below:

① Extensometer imposed on a test piece

In the case of fatigue tests in air, it is recommended that an extensometer with quartz sticks (LVDT or strain gauge type) is directly imposed on a gauge section of a test piece. The extensometer has to be made so that slip does not occur between the quartz sticks and a test piece during heating or seismic vibration. Methods to prevent slipping are shown below: For details, see Fig. 2.4-4.

(a) Machine the tip of a quartz stick to V-shape so that it contacts the surface of a test piece by two points.

(b) Use an additional quartz stick that embrace a test piece

(c) Use both a metal fitting and an additional quartz stick that embrace a test piece. Also, hook an extensometer by a spring so that vibrations that may be caused by earthquakes, etc. are absorbed.

② Arm shoulder type strain meter

For fatigue test in sodium, the strain meter is the arm shoulder type (LVDT system) which can measure the displacement during the projection (collar) for detection is desirable as shown in Fig2.4-5.

The appearance figure of various strain meters is shown in Appendix 2.4-6, and 7 and 8.

(4) Heating apparatus

Heating apparatus is for heating test pieces up to the temperature at which tests are supposed to be performed. Electric furnaces or high frequency induction heating are recommended. Thermo-couples to measure temperature should be in accordance with JIS C 1602, and "R thermo-couples" of which diameter is 0.3 (JIS Class 2) should be used. Temperature should be controlled by the PID method.

(5) Load measurement apparatus (Load Cell)

Load should be measured by a load cell which is made of elastic material and strain gauges attached on it to detect shear strain. The apparatus should be attached to the upper rod above a test piece or to the lower rod. It should be cooled to be within the specified temperature range.

Accuracy of static strain measurement should be within ±1.0%.

(6) Record

For the recording of stress, strain, and temperature, recorders or an on-line data acquisition system are employed.

① Recorder

Hysteresis loops are recorded by an X-Y recorder. Time histories of stress, strain, and temperature are recorded by X-T recorders and a thermometer.

② On-line data acquisition system

See "2.3 Relaxation test".

A schematic illustration of an on-line data acquisition system is given in Appendix 2.4-9.

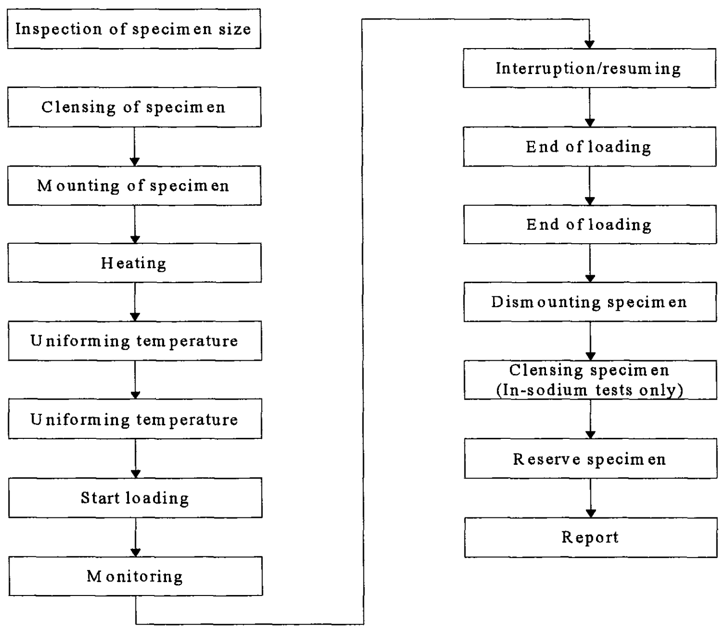
(7) Environment of test machine

In order to assure reliability of data, it is necessary to keep the test apparatus and measurement apparatus in a stabilized environment. It is recommended to confine temperature fluctuation in a test room within 2 degrees Celsius. To achieve this, it is recommended to embrace the test system by a double windshield and limit the temperature fluctuation inside the shield within +-0.5 degrees Celsius. The windshield is to prevent temperature fluctuation due to air conditioning in a room from transferring to test apparatus, which might cause fluctuation of measured load, as well as to improve the accuracy of peak stress data in fatigue tests and stress relaxation data in creep-fatigue tests.

In addition, the quality of long-term tests can be improved by preventing choking of coolant circuit by cleaning the water and by a controlling unit and a water filter unit.

2.4.5 Test methods

Test temperature and loading methods should in accordance with JIS Z 2279.
A standard procedure for fatigue test and creep-fatigue test is shown in the figure:



(1) Inspection of the size of test pieces

Check the report of the inspection when test pieces are delivered.
Locations at which size should be measured are indicated in Fig.2.4-9.

(2) Cleansing of test pieces

See “2.1 Tensile test”

(3) Method of test piece mounting

① Accuracy of center

It should be confirmed more than once a year that eccentricity and horizontalness are less than 0.05mm and 0.01mm, respectively. Measure as shown in Fig. 2.4-10: In the case of an electro serve system, measure the eccentricity of the lower rod of the machine at every 90 degrees. In the case of electro servo motor system, measure eccentricity by attaching filler metals between upper and lower rods; because they do not rotate. Measure bending stress if necessary. The same method as shown in Fig. 2.4-11 can be applied to a hydro-servo system and an electrical servo motor system. Bending stress can be measured by detecting bending eccentricity, using four strain gauges attached to the test piece in four directions, neighboring two forming a right angle. Small load that keeps a test piece within elasticity is given and eccentricity is measured. It is then transformed using the equation in Fig. 2.4-11.

② Mounting a test piece

In mounting a test piece, only minimum load that is necessary to mount a test piece should be applied and no excessive load must be applied. Grips should be designed so that no excessive torsion moment is applied when a test piece is mounted to a machine.

③ Mounting an extensometer

When mounting an extensometer, care should be taken that the upper and lower quartz sticks push a test piece with an identical force, in order to prevent the extensometer from dropping off or slipping during a test. When mounting an extensometer before heating, thermal expansion should be accounted for and the distance between the two quartz sticks should be a gauge length at the test temperature.

When mounting an extensometer after heating, the distance between the upper and the lower quartz sticks should be identical to the gauge length of the test piece. In addition, an extensometer should be placed in the center of a gauge length, taking account of thermal expansion (Fig. 2.4-12).

(4) Heating method

① In-air fatigue test

Thermo-couples are attached to a test piece both by spot welding and binding string. Spot welding attaches thermo-couples firmly and error in temperature measurement is small. However, the welding spots tend be an initiator of a crack. On the other hand, binding string method does not have this disadvantage. However, in terms of bonding and measurement error, spot welding is better. Adjustment should be done according to JIS Z 2279 so that temperature distribution within the parallel portion is less than ±5 degrees Celsius. In the case of induction heating, the configuration of the tip of the thermocouples should be plate rather than sphere, because the former is better in terms of measurement error. Thickness of approximately 0.3mm and diameter of 1mm is recommended (Fig. 2.4-13). The tip of the thermocouples should be exchanged for every test, in principle.

(a) Preliminary temperature distribution measurement (Fig. 2.4-14)

A pair of thermo-couples is attached to the R portion of a preliminary test piece (configuration and material should be identical to the one used in actual tests) by spot welding. Thermo-couples for monitoring temperature distribution are to be attached to the upper, middle and lower parts of the parallel portion. Heat up the test piece by induction heating and adjust the temperature difference among the three pairs of thermo-couples to be within ±5 degrees Celsius (In the case of electric furnace, power balance of upper, middle, and lower furnaces should be adjusted. In the case of induction heating, the configuration of a work coil should be adjusted after cutting power off). An example of methods of manufacturing and adjusting an induction heating coil is shown in Appendix 2.4-10. Temperature is controlled through the thermocouple attached to the R portion (The temperature at this portion can be different from the target value by ±5 degrees Celsius.

(b) Temperature control in actual tests (Fig. 2.4-14)

A pair of thermo-couples is spot welded to the R portion for controlling temperature and another pair of thermo-couples for monitoring temperature is bound to the center of the parallel portion where temperature is controlled (Fig. 2.4-15). Temperature distribution is assured by further adjusting a work coil that has been pre-adjusted in the case of induction heating, by balancing the power of the upper, middle, and lower furnaces in the case of using electric furnaces. Temperature at the R portion can be different from the target temperature in the parallel portion by more than ±5 degrees Celsius.

(c) Hold time for uniforming temperature

Until the output of an extensometer is stabilized, test should not be begun.

② In-sodium fatigue test

Temperature control of the fatigue test in sodium measures the temperature of the entrance of the test piece for fatigue test with a bellows by the well type K thermocouple, as shown in Fig. 2.4-16, and it controls the temperature of fluid sodium by the heater of a sodium loop. In this case, the heating furnace of a testing apparatus is used as a reserve heating furnace so that the difference of temperature of entrance, exit of the fluid sodium of a bellows test piece may not become ±5℃ or more. Soaking time after a temperature raising be time until the output value of a strain meter is stabilized.

(5) Loading method

From mounting of a test piece to just prior to testing, machine should be kept load controlled and no load should be applied. Get every recorder ready and input test conditions to a controller and start a test. During testing, error between input waveform and output waveform should be within ±3%.

(6) Recording fatigue test data

Hysteresis loops are to be recorded by an on-line data acquisition system or an X-Y recorder. Initial 10 cycles are to be recorded and following cycles should be recorded on a logarithm basis, for example, 12, 14, 16, 18, 22, 25, 30, 35, 40, 45, 50, 55, 60, 70, 80, 90, 100, 120, 140, 180, 200 (cycle)・・・. In the case of creep-fatigue tests, strain and stress during hold time should be recorded on a logarithm basis, for example, 0, $2.78x10^{-5}$, $5.56x10^{-5}$, $8.33x10^{-5}$, $1.39x10^{-4}$, $2.78x10^{-4}$, $5.56x10^{-4}$, $8.33x10^{-4}$, $1.39x10^{-3}$,・・・(hr).

(7) Record of time history of stress, strain, and temperature

Time history of stress, strain, and temperature should be recorded by an X-Y recorder, etc.

(8) Monitoring of test

① During 10 cycles immediately after the start of a test (until test becomes stable), the test should be carefully observed so that mal-functioning such as bucking, unnatural hysteresis loops, slip of an extensometer can be immediately detected. After 10 cycles, test should be monitored periodically.

② In sodium test, test conditions, such as the principal part temperature of a sodium loop and flux, are recorded in addition to record of fatigue-test data, and a loop operation state is always supervised and recorded.

(9) Interruption and resume of test

When test was interrupted by some abnormal reasons, the reason must be clarified and eliminated. Then, the temperature, strain, etc just before interruption should be reproduced and test should be resumed. When discontinuous increase or decrease of load is detected after resuming a test, because of slipping of an extensometer, etc, or when abnormal deformation (buckling) was detected, the test should be abandoned.

The reason of interruption should be recorded.

(10) Termination of test

Number of cycles to failure is to be determined as shown in Fig.2.4-17 according to JIS Z 2279. Additional cycles are imposed and after the termination of test, cycles to failure is determined.

(11) Reservation of test piece

After the termination of a test, a test piece should be wrapped up by paper towel indicting test piece number, test conditions, etc and reserved in a decicator.

(12) Determination of number of cycles to failure

Number of cycles to failure should be determined according to JIS Z 2279.

① Cyclic hardening material

Number of cycles to failure is determined as cycles at which tensile peak stress becomes 75 % of its stabilized value, as shown in Fig. 2.4-17.

② Cyclic softening material

When a tensile peak stress continuously decrease and a stabilized state is not clear, the decreasing behavior from the middle of the test to the end of the test except just before rupture should be approximated and extrapolated by liner relationship (y=ax+b). The cycle at which a tensile peak stress becomes 75% of the extrapolated value is defined as a cycle to failure.

(13) Determination of location of failure

In the case of a base metal test piece and weld metal test piece, gauge length is divided to four portions. Two portions in the center are termed A, the outer two portions are termed B, outside of the gauge length is termed C, and the location an extensometer is pushed to is termed D, and the location where thermo-couples are attached.

In the case of welded or dissimilar welded specimen, same as tensile tests in 2.1.

2.4.6 Report of test results

Following items should be reported. Typical datasheets and graphs are shown in Appendix 2.4-11 –24. For in-sodium tests, see Appendix 2.4-15. Moreover, test result is collected after computing the strain range by the method shown in Appendix 2.4-15 in sodium test.

(1) Material (Heat No.)
(2) Product form and configuration of a test piece (including history of a test piece)
(3) Specification of test machine
(4) Test conditions
  ① Test temperature
  ② Load control or strain control
  ③ Total strain
  ④ Strain rate
  ⑤ Hold time (creep-fatigue tests)

(5) Test method

(6) Test result

① Number of cycles to failure

② Values at half life or its vicinity (Total strain range, inelastic strain range, and stress range)

③ Hysteresis loops at the beginning of a test, at a stabilized state of a test, at half life of a test

④ Continuous change of stress and strain during a test

⑤ Location of failure, etc.

(7) Miscellanies, abnormal things during a test

2.4.7 Adding to test result to the database

See "2.1 tensile tests"

2.4.8 Normative reference

① Japanese Industrial Standard JIS B 0031-1994

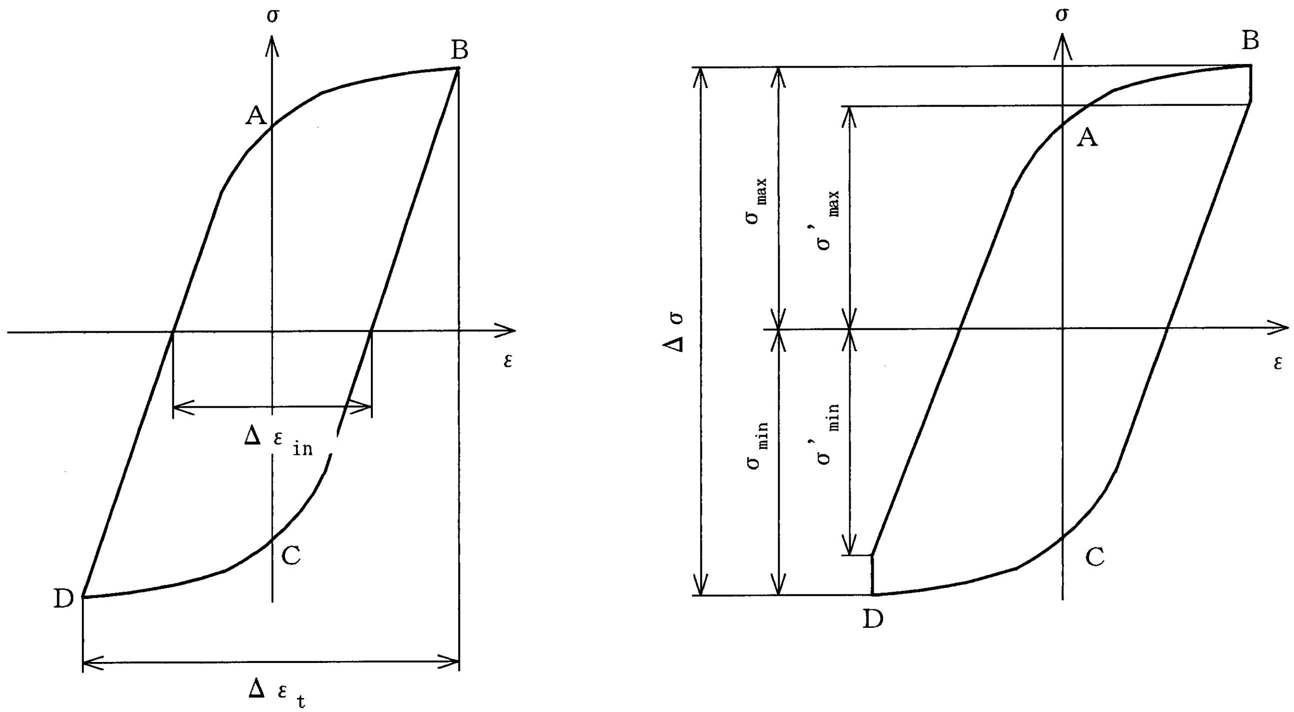
② Japanese Industrial Standard JIS B 0601-1994

③ Japanese Industrial Standard JIS C 1602-1995

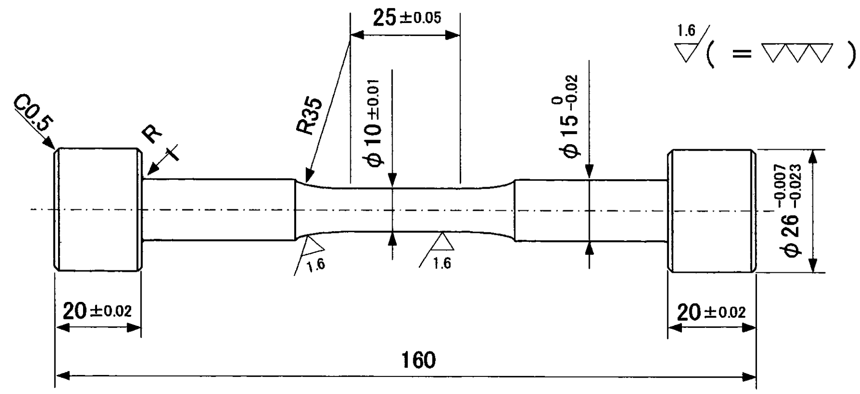
④ Japanese Industrial Standard JIS Z 2279-1992

Table 2.4-1 Definition of terms for Low cycle fatigue test

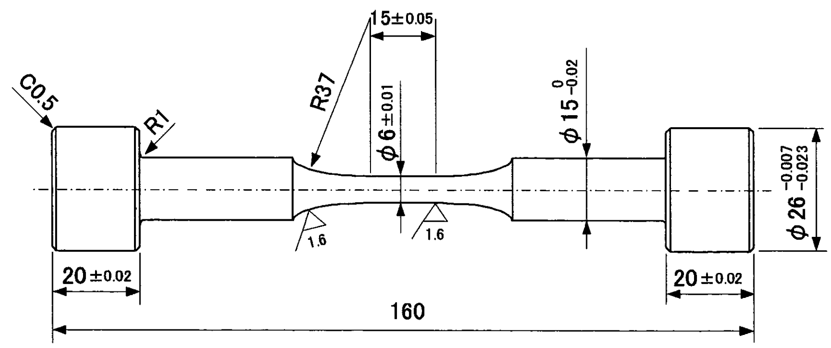
No.	Term	Standard sign	Explanation
1	Cycle	—	From strain 0 to 0 by passing the maximum value and minimum value. (Figure 2.4-1 A→B→C→D→A)
2	Number of cycles	N (cycles)	The number of strain cycles during creep fatigue test and fatigue test.
3	Hysteresis loop	—	A Loop that illustrates the relation between the stress and strain observed during the fatigue test. (Figure 2.4-1 reference)
4	Strain rate	ε_t (%/sec)	The Value is obtained by dividing the total strain range by a time required for one half of the period.
5	Frequency	f (Hz、cpm)	The number of complete cycles of a periodic process occurring per unit time.
6	Strain hold time	t_h (hr)	Time that strain in one cycle becomes constant by fatigue test apparatus of strain control type of trapezoid waveform.
7	Total strain range	$\Delta\varepsilon_t$ (%)	The Value is obtained by dividing the difference of the gauge length after deformation and the initial gauge length of the test piece by the initial gauge length of the test piece.
8	Inelastic strain range	$\Delta\varepsilon_{in}$ (%)	The range of strain in case stress is 0 in a stress-distortion hysteresis loop [near $1/2N_f$]$1/2N_f$. (Figure 2.4-1Reference)
9	Elastic strain range	$\Delta\varepsilon_e$ (%)	The value is obtained by subtracting the inelastic strain range from the total strain range. (Total strain range) — (Inelastic strain range)
10	Number of cycles to failure	N_f (cycles)	Chapter 2.4.5(12) Reference
11	Time to failure	t_f (hr)	Time until it results [from load start] in a number of cycles to failure.
12	Max.,min. Stress	σ_{max} σ_{min} (N/mm^2)	The absolute value of the maximum stress (tensile side), and the minimum stress (compression side) [in each cycle]. (Figure 2.4-1 Reference)
13	Max.,min. Stress after relaxation	σ'_{max} σ'_{min} (N/mm^2)	The absolute value of the maximum stress(tensile side), and the minimum stress (compression side) [after strain maintenance] (Figure 2.4-1 Reference)
14	Stress	σ (N/mm^2)	The value is obtained by dividing the axial load of the difference of the test piece by the original cross section of the test piece.
15	Stress range	$\Delta\sigma$ (N/mm^2)	$\sigma_{max} + \sigma_{min}$
16	Initial stress strain curve	—	A stress strain curve until it reaches the beginning from load start at the maximum strain point or the minimum strain point (Monotonic Curve).



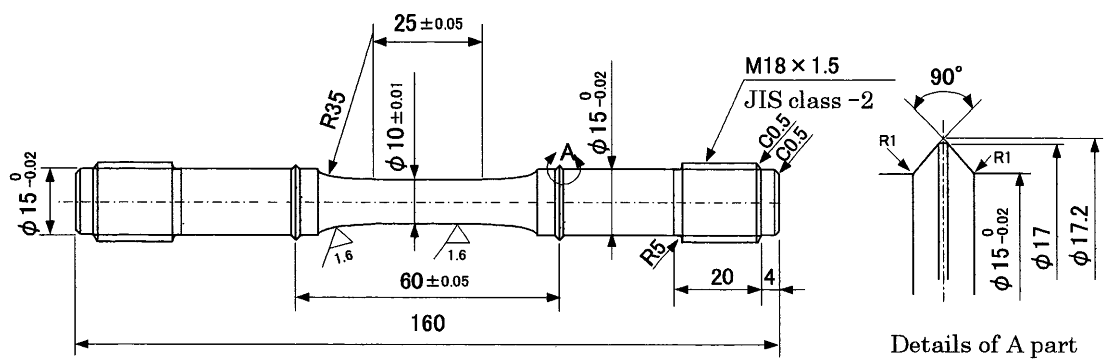
Reference Fig. 2.4-1 Typical explanation of stress strain wave form chart



10φ. Button type

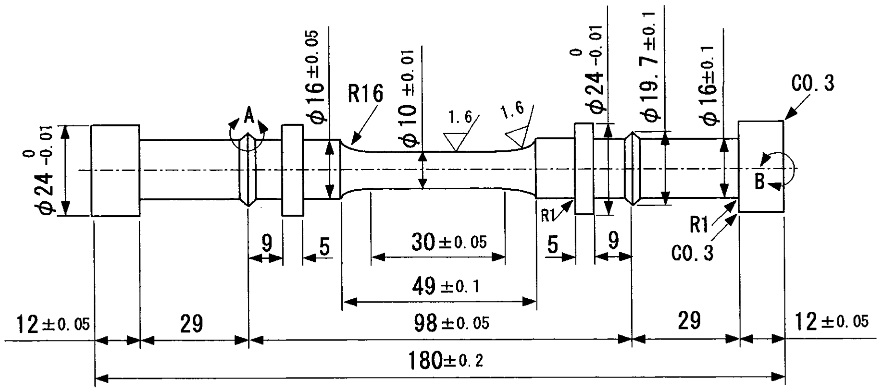


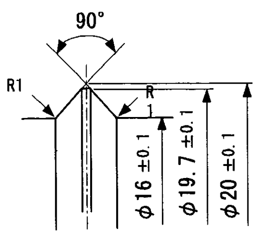
6φ. Button type



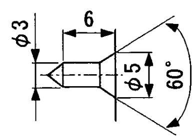
10φ. Screw type

Fig. 2.4-1 Configuration of test piece for fatigue test in air



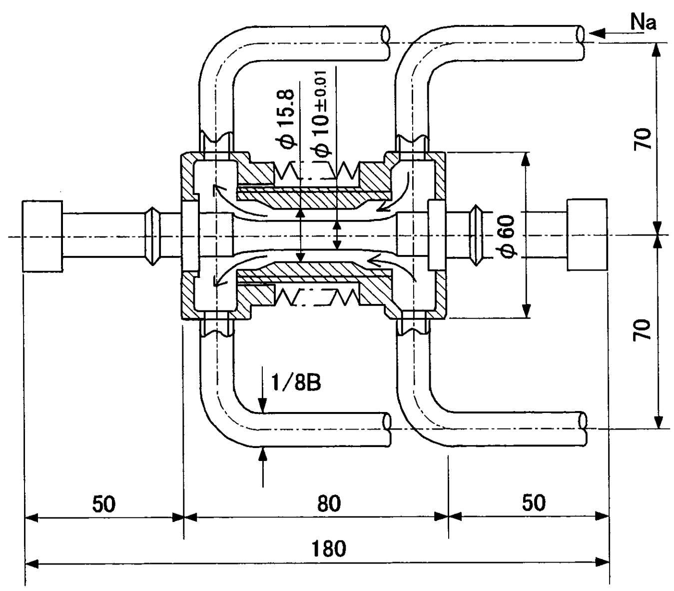


Details of A part



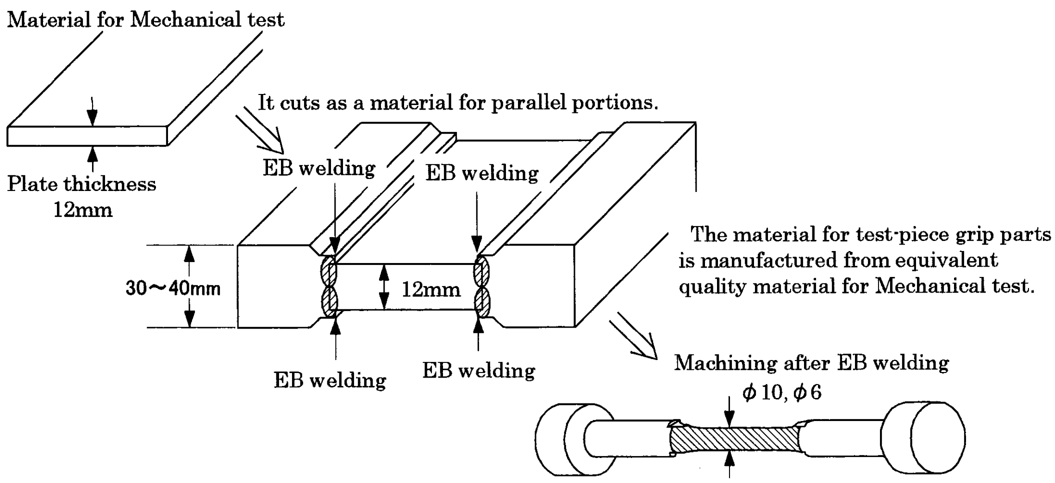
Details of B part

Test piece details



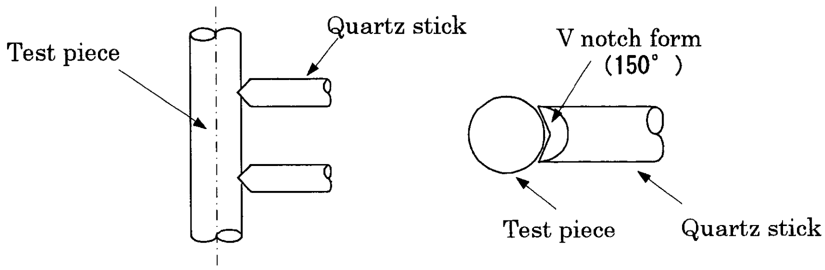
The state which attached the bellows

Fig. 2.4-2 Configuration of test piece for fatigue test in sodium

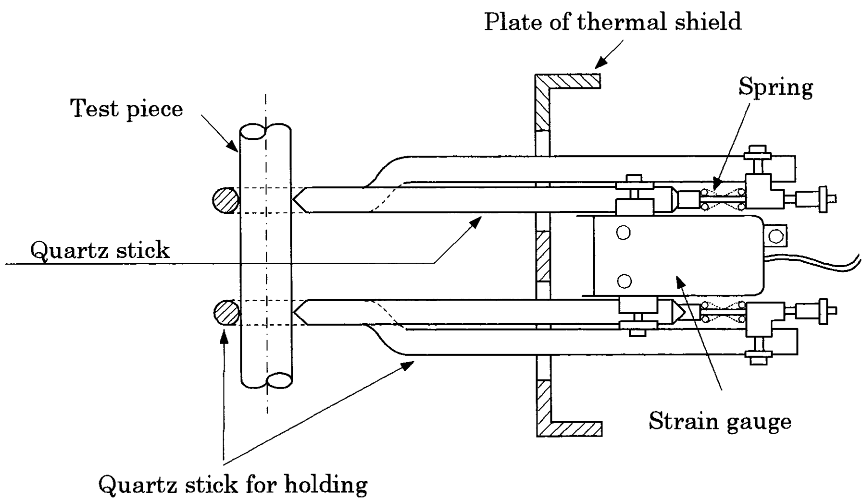


The example of a test-piece manufacture
in the case of extracting a test piece for fatigue test from a thin steel plate

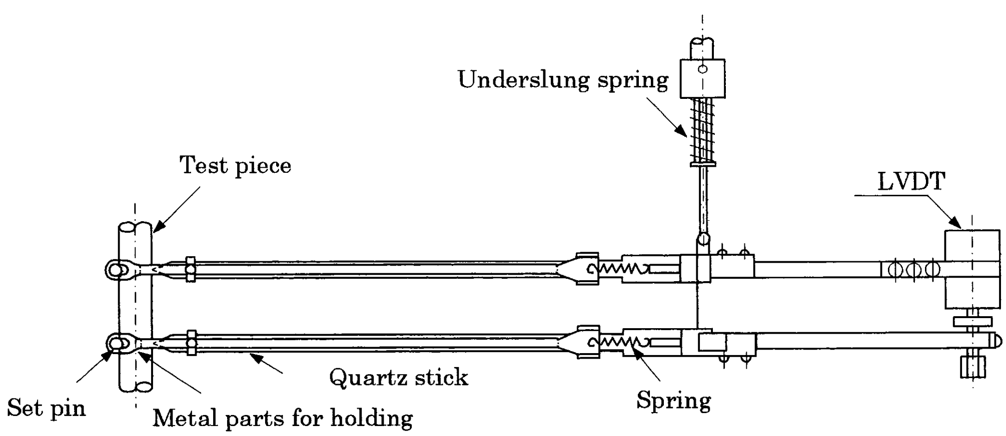
Fig. 2.4-3 Example of manufacture of special test piece for fatigue test



The example of the part which strain gauge pushes



Example of use of the quartz stick for holding test piece



Examples of use, such as the underslung spring, and metal parts for holding

Fig. 2.4-4 Preventive measures to slipping of the part which strain gauge pushes

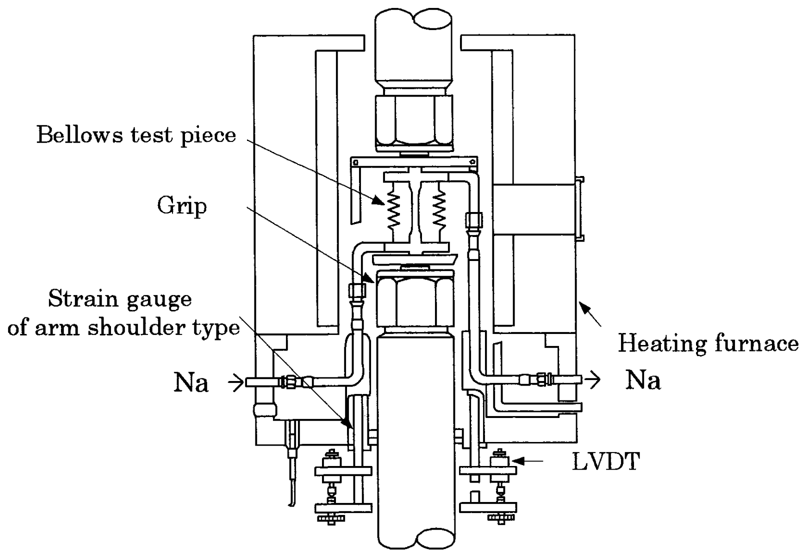


Fig. 2.4-5 Attachment figure of strain gauge of arm shoulder type

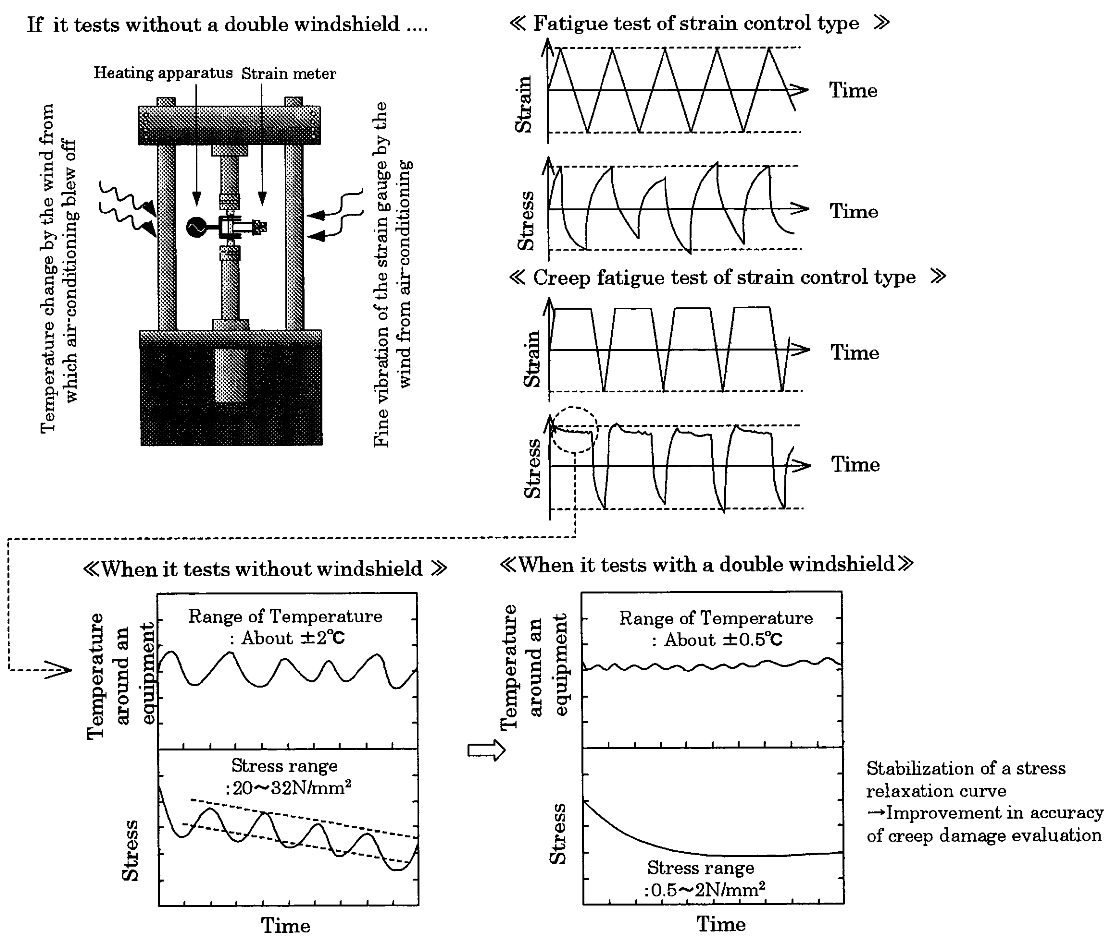


Fig. 2.4-6 Example of improvement of testing accuracy by double windshield

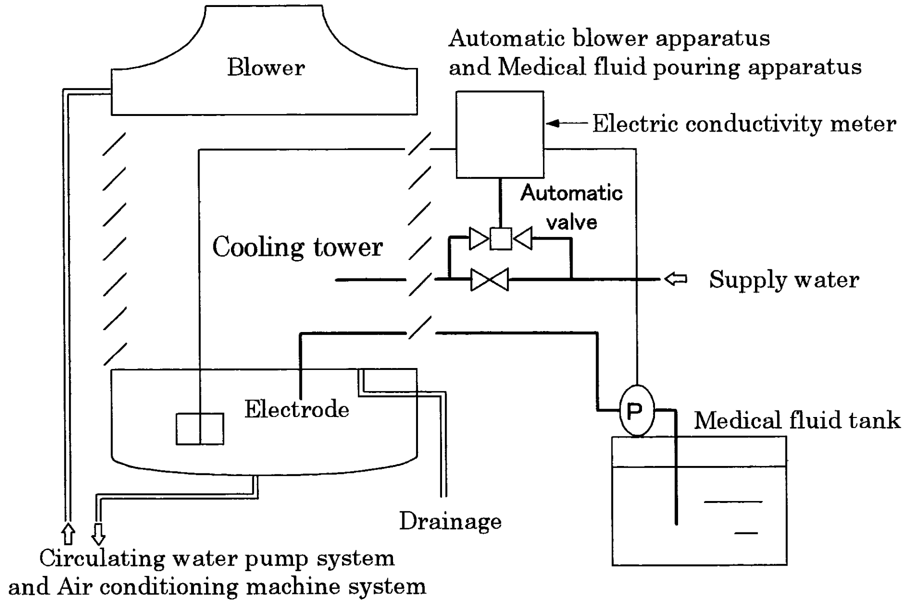


Fig. 2.4-7 Cooling water management system

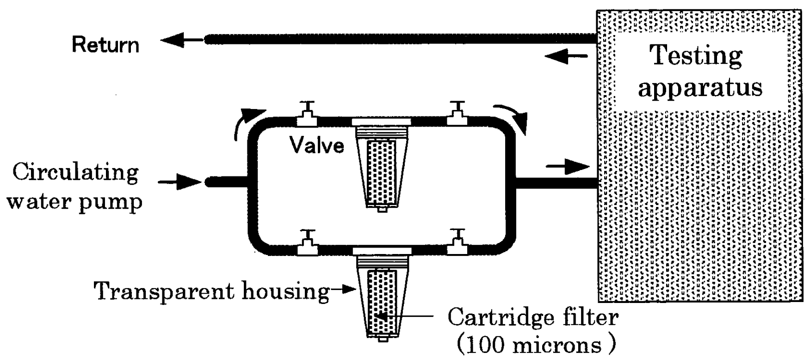
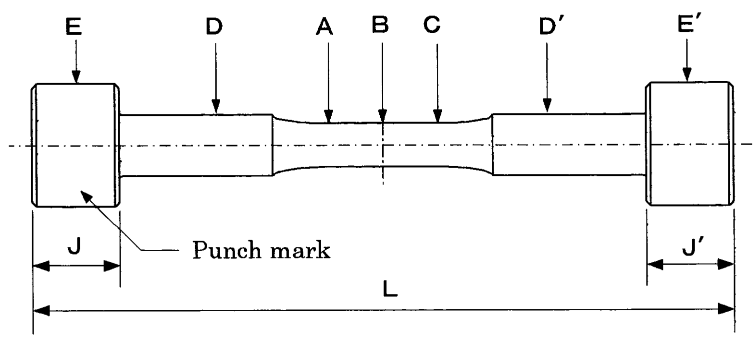
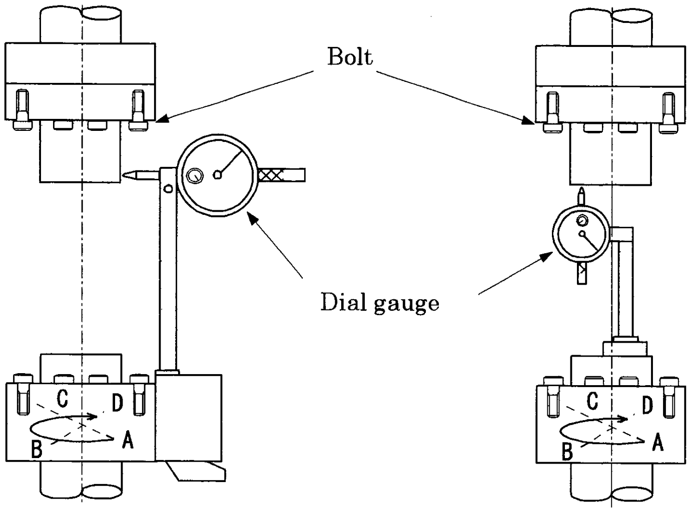


Fig. 2.4-8 Water filter unit



A, B, C, D, D′ , E, E′ :Measurement of orthogonal 2 direction
J, J′ , L :Measurement of two positions which become axial symmetry

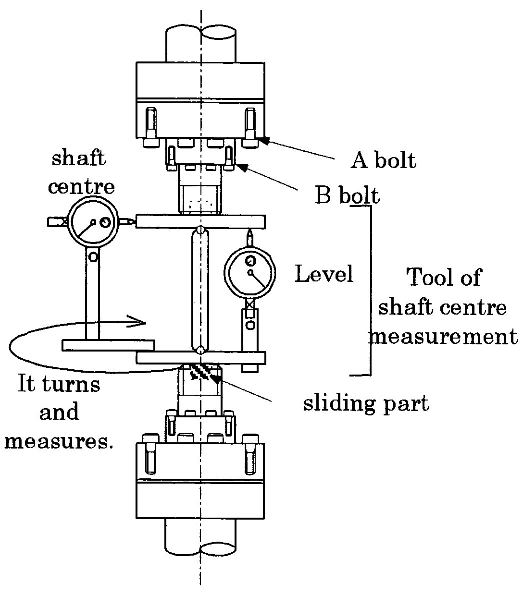
Fig. 2.4-9 Part of measurement of test piece for fatigue test



Shaft centre measurement
between vertical rods

Level measurement
between vertical rods

Hydraulic servo Type

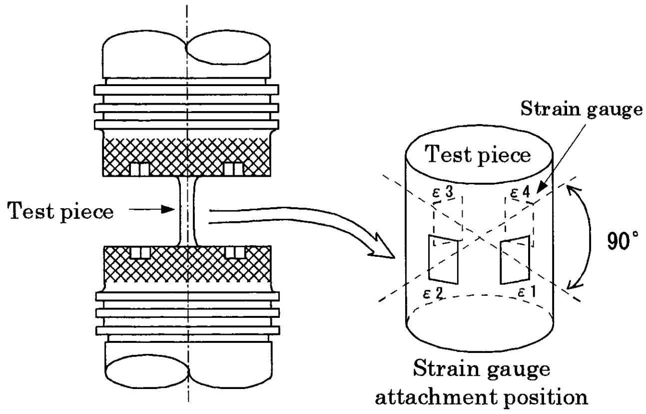


Electric servo motor Type

《Adjustment method of a shaft centre》

When shaft-centre accuracy is 0.05mm or more, in the case of the hydraulic-servo system, the bolt of the upper rod (fixed rod) is loosened. Then it is adjusted, by a plastic hammer, and the bolt is retightened, and a shaft centre and the degree of level are measured. In the case of an electric servo motor system, after loosening A bolt of an upper rod, shaft centre is adjusted by the same method as a hydraulic servo system. For the degree of level, B bolt is loosened and the same adjustment as the above is performed. When it cannot be adjusted, metal foil is put on. Moreover, after adjusting the degree of level previously, it is good to adjust the shaft centre.

Fig. 2.4-10 Measurement method of shaft centre accuracy



$$B(\%) = \frac{2\sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_4)^2}}{\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4} \times 100$$

Fig. 2.4-11 Measurement method of bending strain ingredient of test pieces

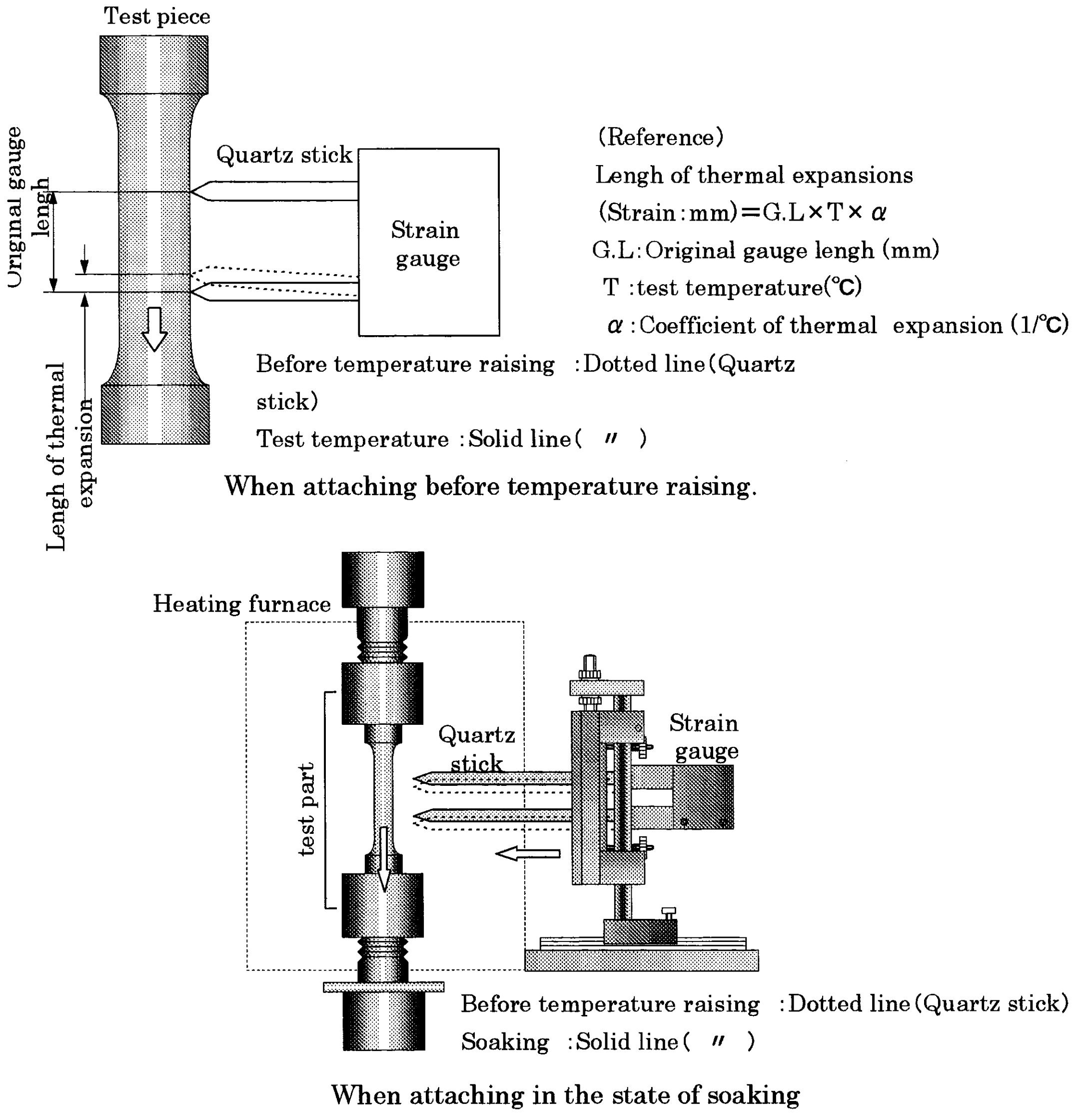


Fig. 2.4-12 Method of strain gauge attachment

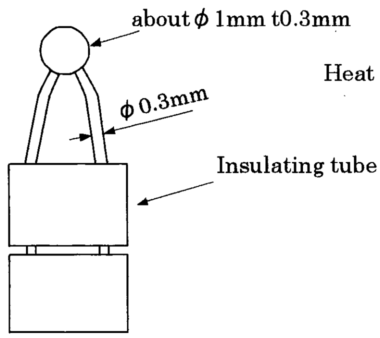


Fig. 2.4-13 Form of thermocouple tip part

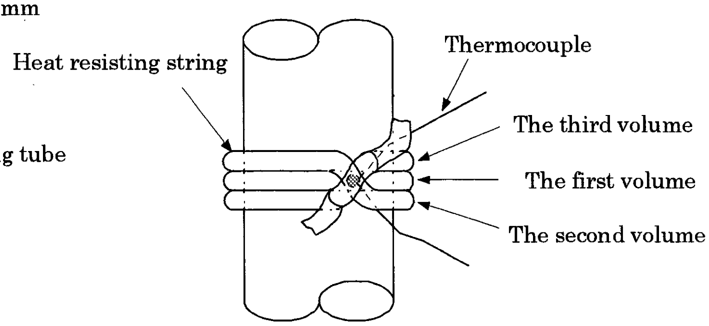
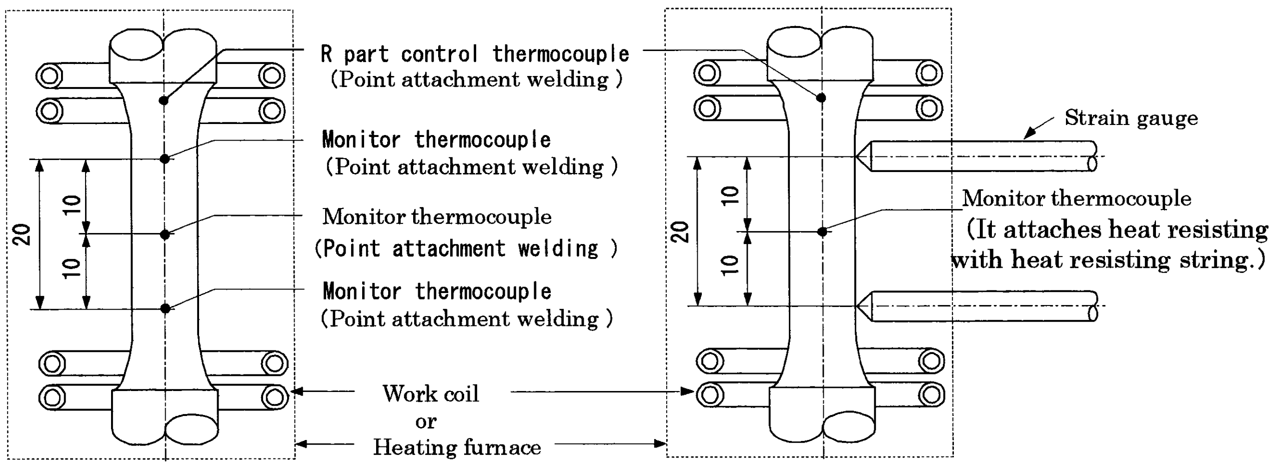


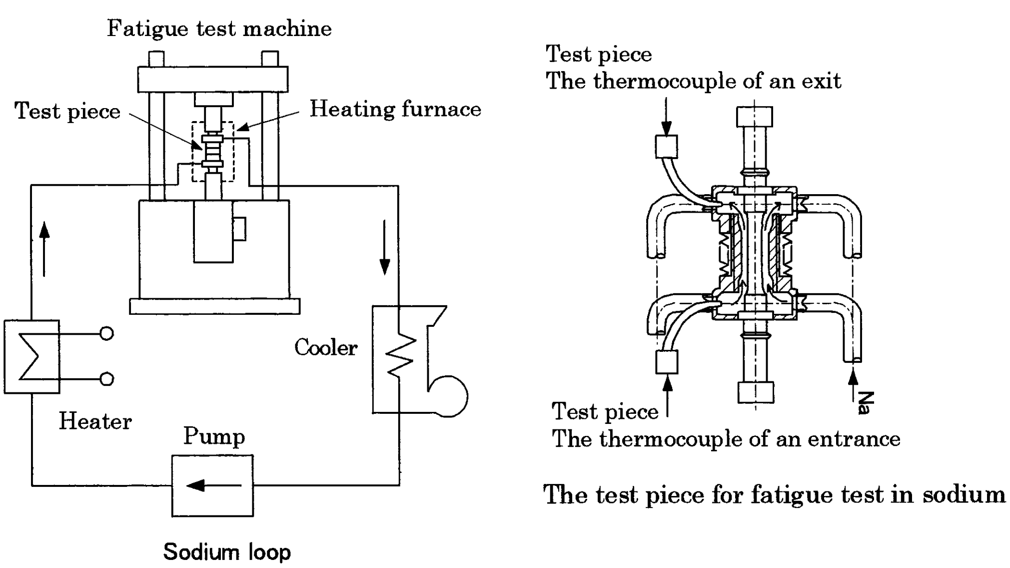
Fig. 2.4-15 Method of thermocouple attachment



The measuring method of the temperature distribution before test start

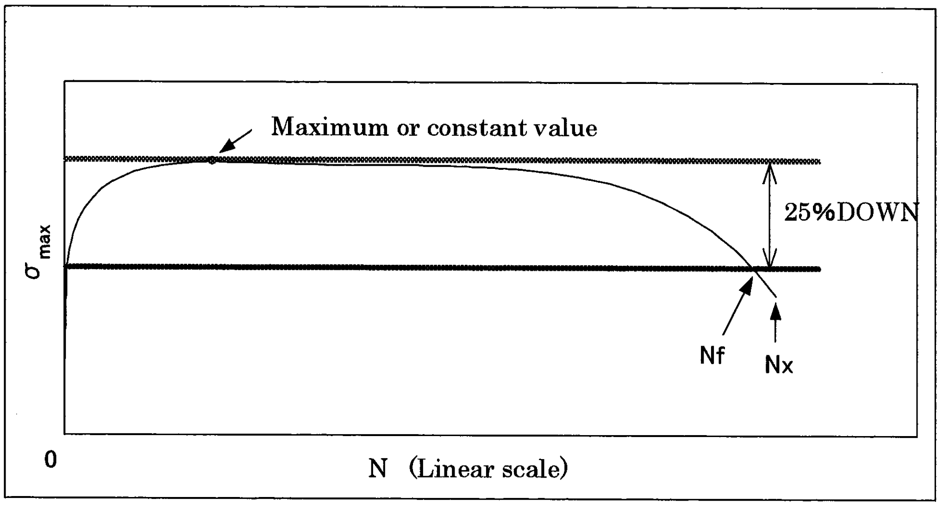
The temperature control method after test start

Fig. 2.4-14 Method of temperature control

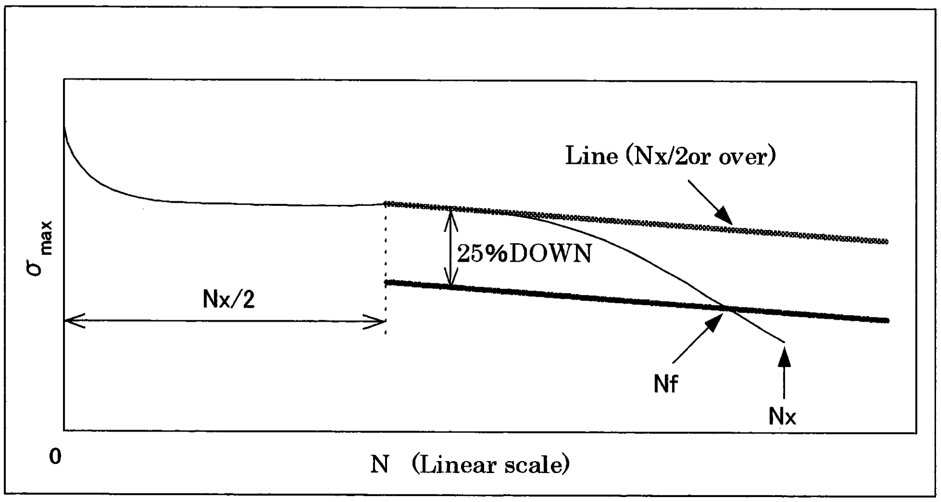


The test piece for fatigue test in sodium

Fig. 2.4-16 Temperature measurement control method for fatigue test in sodium



Hardening material



Softening material

Fig. 2.4-17 How to determine number of cycles to failure

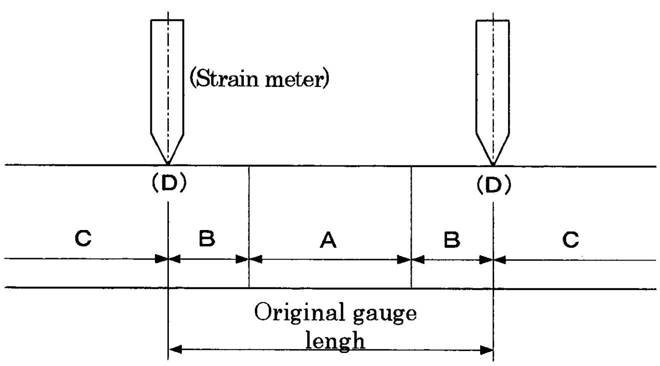


Fig. 2.4-18 Indentification of location of failure
(Base material and welding metal)

Acknowledgements

We wish to thank Dr. Tai Asayama of Structural mechanics Research Group and Mr. Seiichi Kawashima, Mr. Koichi Suzuki, Mr. Koichi Kuroko and the staff of Joyo Industry Co. Ltd., for their cooperation and support in the preparation of this manual.

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[3] Masaki Kitagawa et al, "VAMAS Low Cycle Fatigue Round Robin Test", The Iron and Steel Institute of Japan, Tetsu-to-Hagane, 78^{th} year, Issue No. 9 (1992)

[4] Ito et al, "Deterioration of R thermocouples after long hours of creep test" National Research Institute for Metals (1986)

[5] Komine et al, "Summary of test techniques for the standardization of fatigue test methods for FBR structural materials
PNC TN9440 91-004(1991)

Appendix2.1 Tensile test

Appendix2.1-1 Definition of terms for welding (common)
Appendix2.1-2 A specification list of a tensile test apparatus
Appendix2.1-3 Composition figure of the tensile test apparatus in air
Appendix2.1-4 Configuration of the grip part of test piece for tensile test
Appendix2.1-5 Composition of the online data collection system for tensile test apparatus
Appendix2.1-6 How to determine the cross sectional area of arc section test piece
Appendix2.1-7 FBR metallic materials test data sheet (tensile)
Appendix2.1-8 Tensile test data (Graph)
Appendix 2.1-9 Test data-processing system of structure materials test(SMAT)

Appendix2.1-1 Definition of terms for welding (common)

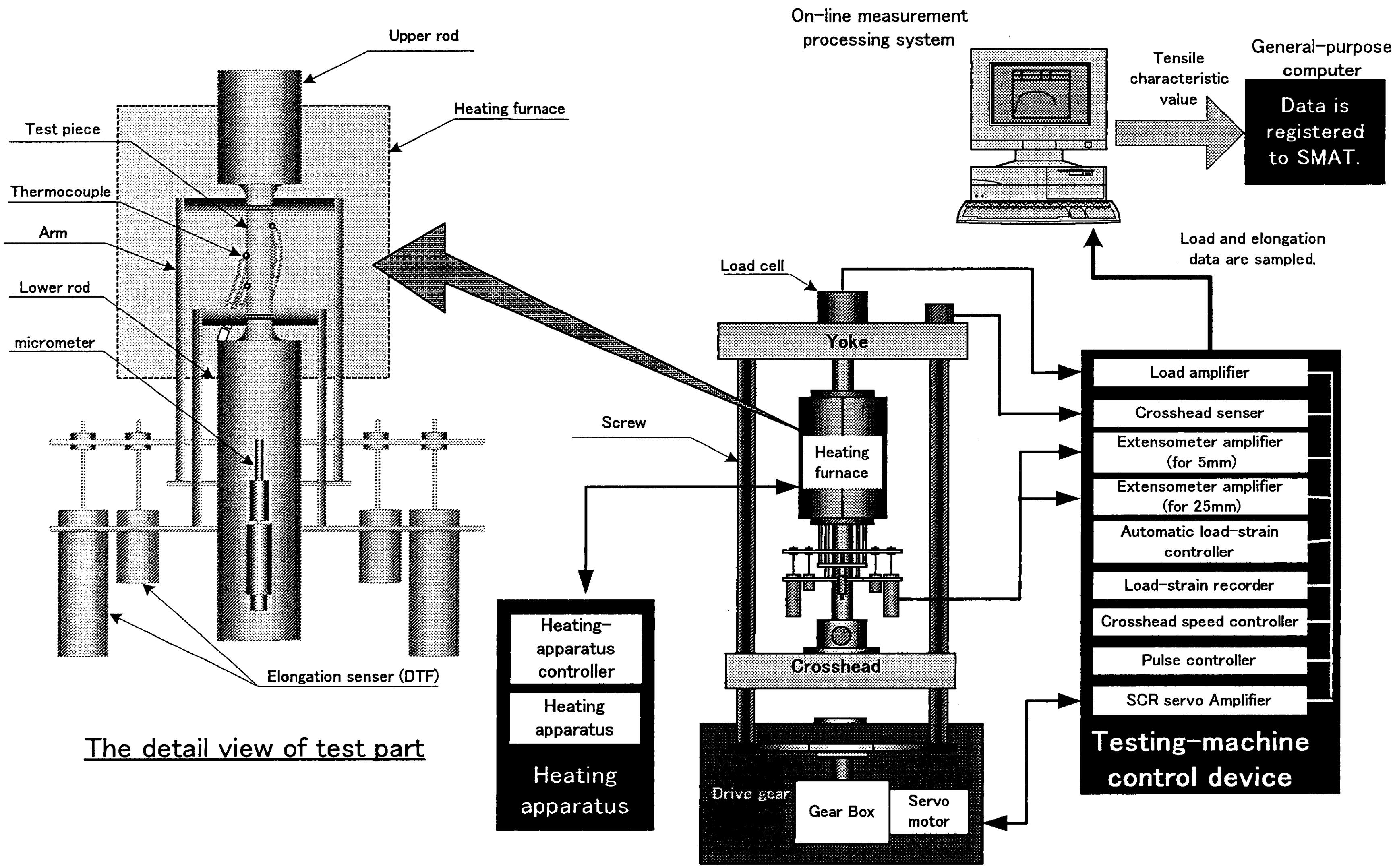
No.	Terms	Standard symbol	Definition
1	Welding	–	The process of joining two or more material parts together by applying heat or pressure, or both, to form one continuous body.
2	Manual Welding	–	Welding performed by hand.
3	Automatic Welding	–	Continuous welding done by equipment that does not necessarily need the presence of an operator
4	Electron Beam Welding	E B W	Welding by using the heat created by the direct impact of a high intensity electron beam in vacuum.
5	Shielded Metal Arc Welding	–	This process uses a covered electrode.
6	Submerged Arc Welding	S A W	Welding using arc heat that is produced during flux between the welding wire and base material.
7	Tungsten Inert Gas Welding)	T I G	Inter gas arc welding using a non consumable electrode usually of Tungsten or Tungsten alloy.
8	Metal Inert Gas Welding	M I G	Solvent pole type electrode inert gas arc welding, using a welding wire as electrode.
9	Plasma Arc Welding	P A W	This process uses plasma arc heat generated between the electrode and the base material.
1 0	Covered Electrode	–	Flux coated electrode used for arc welding. Also referred to as electrode.
1 1	Core Wire	–	Metal wire of the covered electrode.
1 2	Shielding Gas	–	The gas used to cover the arc and molten metal during welding and to prevent the air from entering into the weld atmosphere.
1 3	Filler Metal	–	Metal (materials) added during welding.
1 4	Weld Zone	–	General term for the area containing weld metals and heat affected area.
1 5	Heat-affected Zone	–	Area of the base material not melted, but its structure, metallic characteristics and mechanical properties have been changed due to the heat from welding/cutting.
1 6	Deposited Metal	–	Metal moved from filler metal to weld zone.

Appendix2.1-1 (continued) Definition of terms for welding (common)

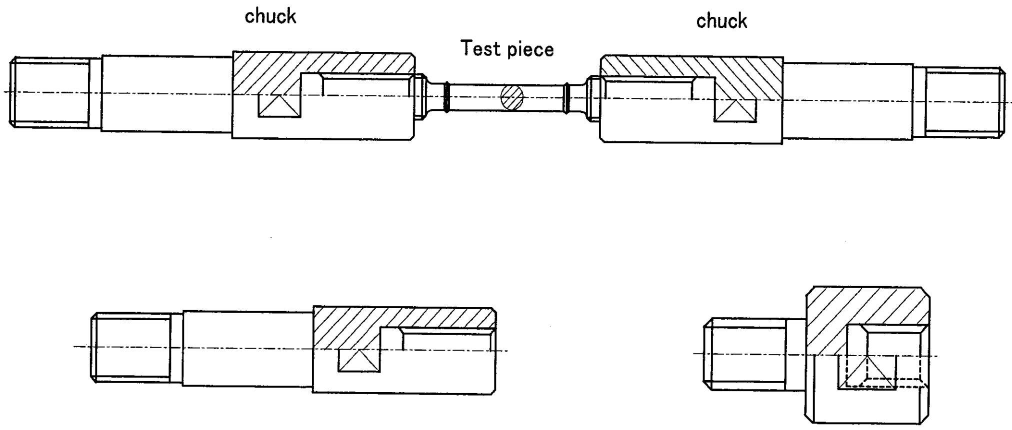
No.	Terms	Standard symbol	Definition
17	Weld Metal	–	Part of the weld zone. Metal that was melted and solidified during welding.
18	Fusion Zone	–	Part of the base materials that was melted during the process.
19	Weld Junction	–	Boundary between the weld zone (weld metal) and the ordinal base material, sometimes including the area around the boundary. If weld metal is not present, as in the case of solid phase welding or soldering for example, it refers to the boundary between the base materials, or the boundary between the filler metal and the base material.
20	Groove Preparation	–	Shape of the groove made in the base material to be welded.
21	Welding Position	–	Position of a welder facing the weld zone during welding. There are flat, horizontal, vertical and overhead positions.
22	Layer	–	Layer of weld metals consisting of one or more passes.
23	Pass	–	One operation performed along the weld joint. The result of a pass is the bead.
24	Interpass Temperature	–	The minimum temperature of the pas before starting the next pass during multiple pass welding. When the interpass temperature is for one-pass one-layer, it is called an interlayer pass.
25	Build-up	–	Welding more than 2 layers performed along the weld line.
26	Preheating	–	To heat the base material before welding or heat cutting operations.
27	Heat Input	H	Amount of external heat applied to the welded part during welding. For arc welding, arc is expressed by the electric energy H(J/cm) generated per unit length(1cm) of arc bead. With the arc voltage E(V), arc current I(A), and welding speed υ (cm/min), it can be expressed by $H=60EI/\upsilon$.
28	Ferrite Content	–	Amount of ferrite composition in the austenite stainless steel weld metals. It can be measured by a magnetic method or by a structural diagram.
29	Postheat Treatment	–	Heat treatment performed on the weld zone or welded structure after welding.

Appendix2.1-2　A specification list of tensile test equipment

<table>
<tr><th colspan="3">Specification / Testing machine No.</th><th>TT-1</th><th>TT-3</th></tr>
<tr><td colspan="2" rowspan="7">The main part of a testing machine</td><td>1) Form</td><td colspan="2">Auto graph DSS-25T</td></tr>
<tr><td>2) Quantity of a balance</td><td colspan="2">MAX.25ton</td></tr>
<tr><td>3) Effective test width</td><td colspan="2">600mm</td></tr>
<tr><td>4) Crosshead stroke</td><td colspan="2">1250mm</td></tr>
<tr><td>5) Crosshead speed</td><td colspan="2">0.005～500mm/min (21 step change)</td></tr>
<tr><td>6) Accuracy of crosshead speed</td><td colspan="2">It is ±0.1% to a total speed.</td></tr>
<tr><td>7) The setting system of crosshead speed</td><td colspan="2">Push button form</td></tr>
<tr><td colspan="2" rowspan="3">Elongation measurement apparatus</td><td>1) Form</td><td colspan="2">The measurement formula of the displacement between the collars of a test piece</td></tr>
<tr><td>2) Senser</td><td colspan="2">DTF: DT-5 type measures even proof stress.
DT-25 type measures power-proof stress or subsequent ones.</td></tr>
<tr><td>3) Measurement range</td><td colspan="2">DT-5type　5,2.5,1,0.5mm/F.S　Accuracy 1%/F.S
DT-2type　25,12.5,5,2.5mm/F.S Accuracy 1%/F. S</td></tr>
<tr><td rowspan="8">Heating apparatus</td><td rowspan="4">For high temperature</td><td>1) Form</td><td colspan="2">Tubular electric furnace of half-rate type</td></tr>
<tr><td>2) Capacity</td><td colspan="2">3KW</td></tr>
<tr><td>3) Control temperature range</td><td colspan="2">300～900℃</td></tr>
<tr><td>4) Control system</td><td colspan="2">PID multi-point simultaneous control system</td></tr>
<tr><td rowspan="4">For super-high temperature</td><td>1) Form</td><td colspan="2">Tubular electric furnace of half-rate type</td></tr>
<tr><td>2) Capacity</td><td colspan="2">5KW</td></tr>
<tr><td>3) Control temperature range</td><td colspan="2">800～1600℃</td></tr>
<tr><td>4) Control system</td><td colspan="2">PID control system</td></tr>
</table>

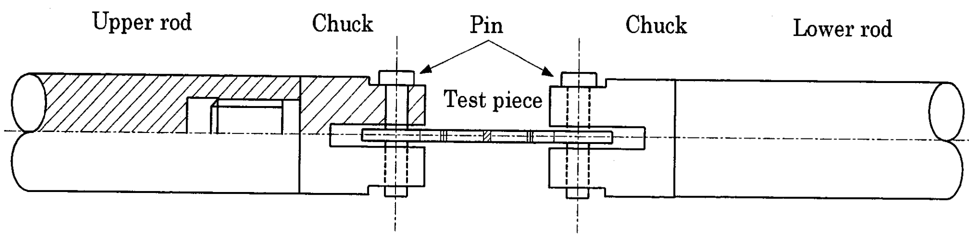


Appendix 2.1-3 Composition figure of the tensile test apparatus in air

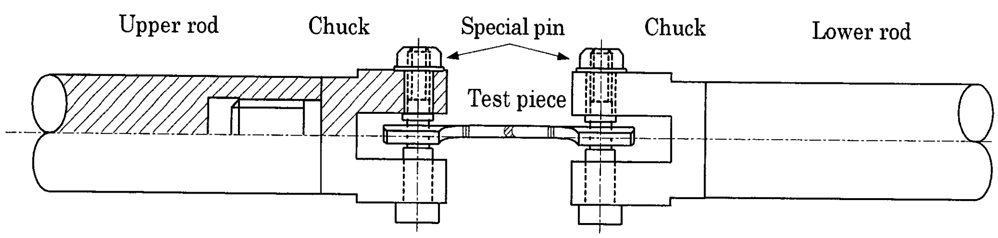


Chuck details for 10ϕ　　　Chuck details for 6ϕ

The chuck attachment figure for bar form test piese

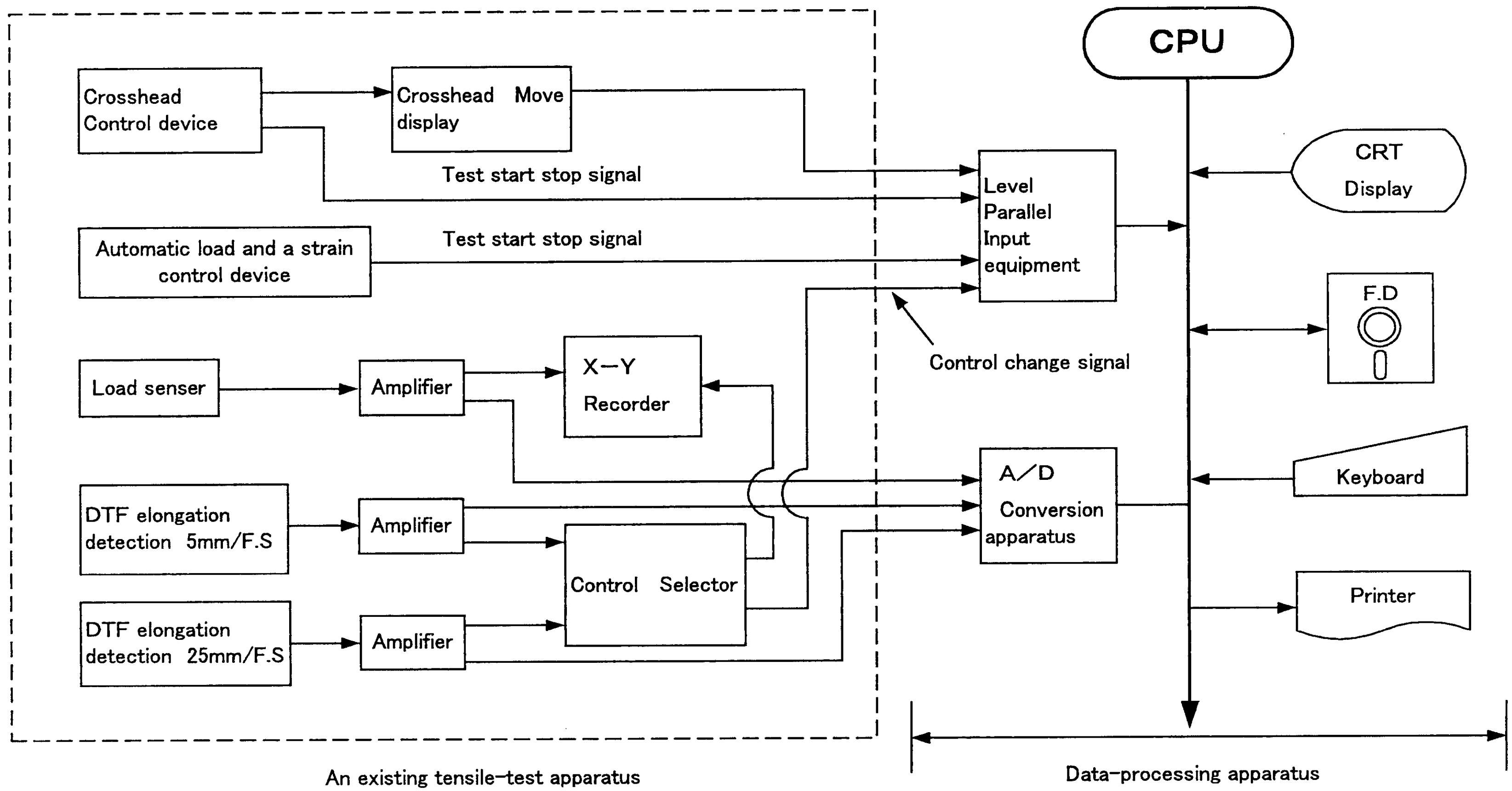


The chuck attachment figure for flat form test piese



The chuck attachment figure for arc secion test piese

Appendix2.1-4 Configuration of the grip part of test piece for tensile test



Appendix 2.1-5 Composition of the online data collection system for tensile test apparatus

Appendix 2.1-6 How to determine the cross sectional area of arc section test piece

The cross sectional area of arc section test piece is computed from the following formulas.

$$S = S_1 + T_1 - S_2$$

$$T_1 = w(r_1\cos\theta_1 - r_2\cos\theta_2)$$

$$S_1 = 2\theta_1/2\pi \times \pi r_1^2 - 1/2 \times r_1\cos\theta_1 \times 2r_1\sin\theta_1$$

$$= r_1^2(\theta_1 - \sin\theta_1\cos\theta_1)$$

$$S_2 = r_2^2(\theta_2 - \sin\theta_2\cos\theta_2)$$

however $r_1\sin\theta_1 = w/2 \rightarrow \theta_1 = \sin^{-1}(w/2r_1)$

$r_2\sin\theta_2 = w/2 \rightarrow \theta_2 = \sin^{-1}(w/2r_2)$

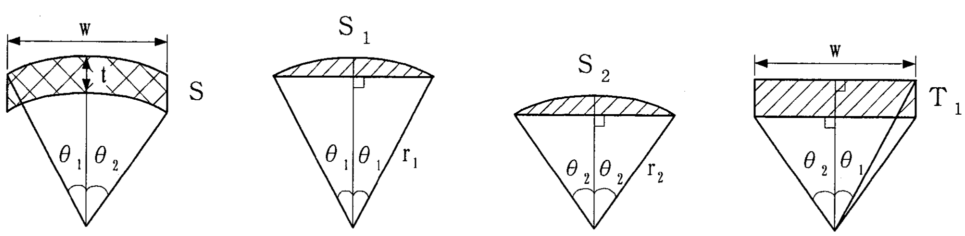
$r_2 = r_1 - t$

r_1 : Outer diameter

r_2 : inner diameter

t : Thickness

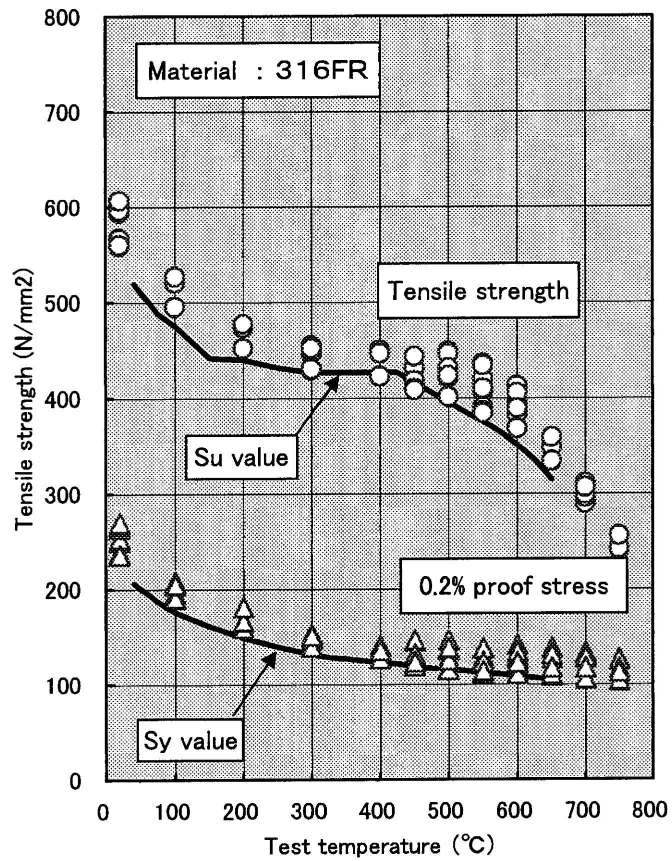
w : Width

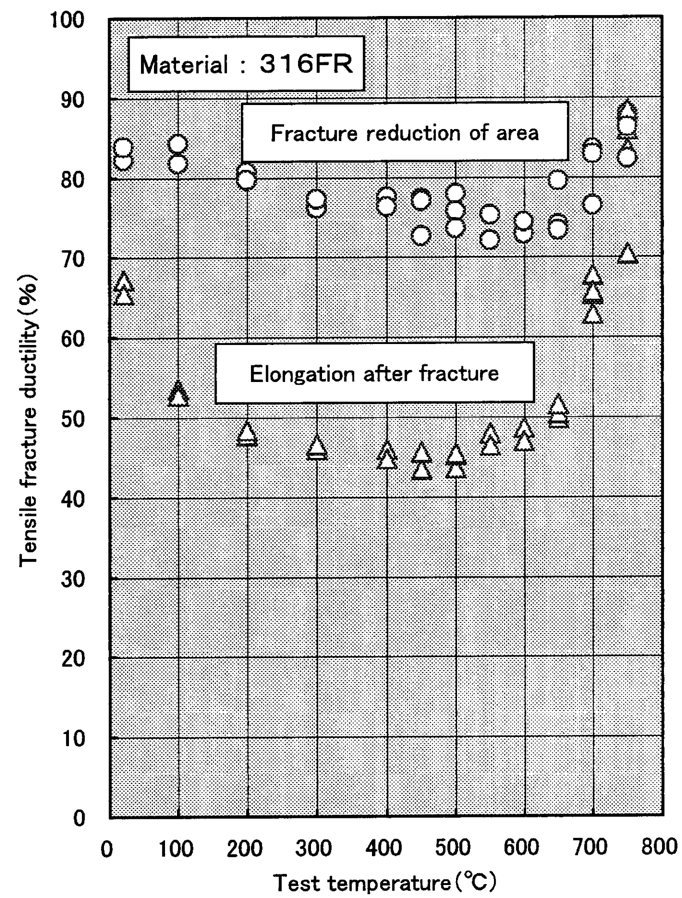


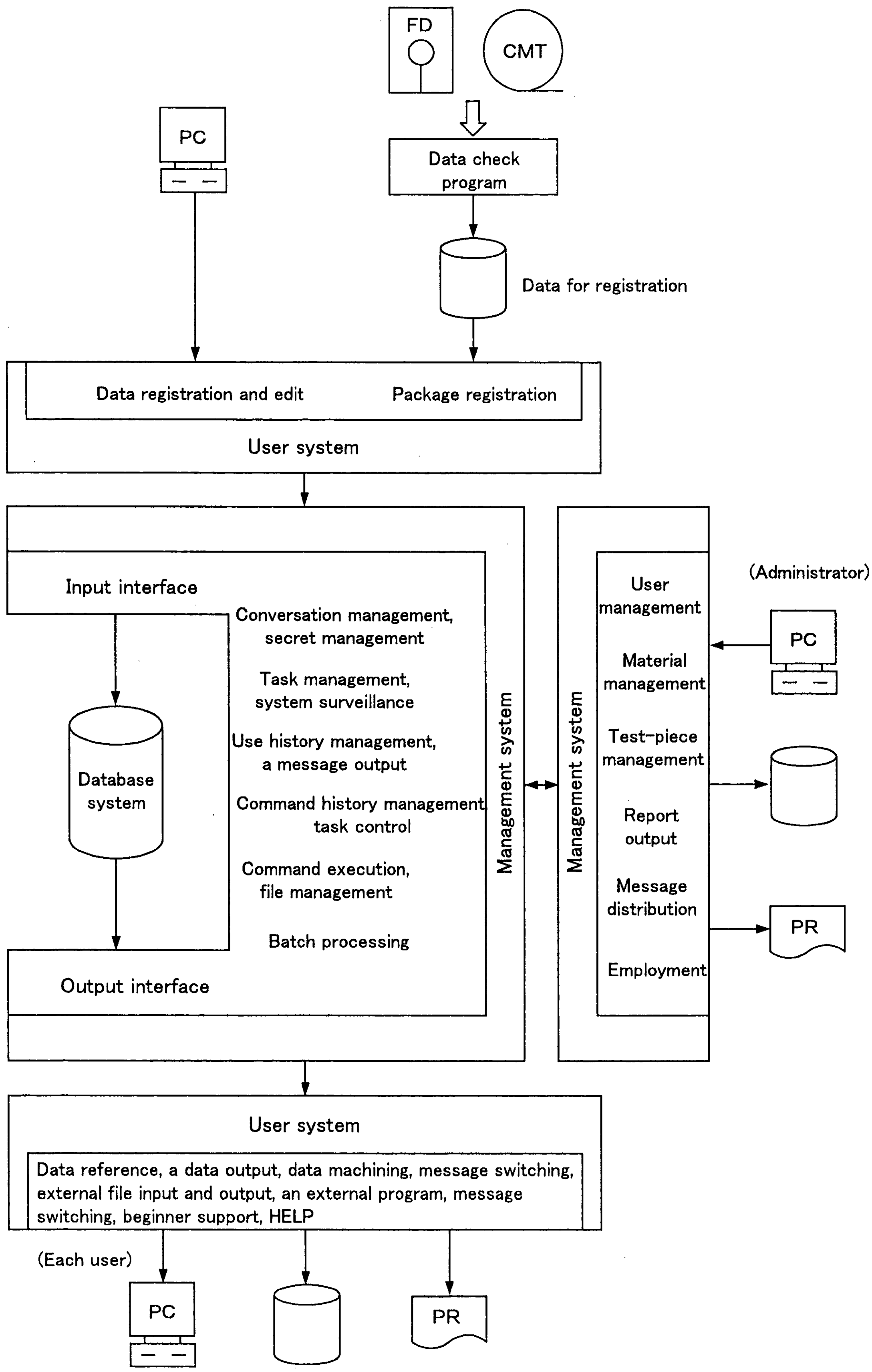
Appendix2.1-7 FBR metallic materials test data sheet (tensile)

Test condition	Strain rate-1(%/min)		Setting strain-1(%)		Strain rate -2(%/min)		Setting strain -2(%)					
1	0.3		3		7.5							
Test piece No	Test temperature	0.2% proof stress	Tensile strength	elongation after fracture	Reduction of area	Fracture position	Upper yield point	Lower yield point	Elongation in 4D	True characteristic		
	(°C)	(N/mm^2)	(N/mm^2)	(%)	(%)		(N/mm^2)	(N/mm^2)	(%)	True fracture stress(N/mm^2)	True uniform elongation(%)	True fracture ductility(%)
END8D2	20	252.8	593.9	67.2	82.2	A				1930.6	380.2	1691.5
END8D3	20	263.6	596.8	65.5	83.9	A				2198.1	384.2	1789.5
END8D4	100	207.8	521.4	53.6	84.3	A				1815.9	306.7	1815.0
END8D5	100	204.8	527.2	52.8	81.8	A				1715.0	298.9	1669.9
END8D6	200	166.6	473.3	47.8	80.7	A				1443.5	292.0	1612.1
END8D7	200	181.3	477.3	48.4	79.7	A				1385.7	292.0	1563.1
END8D8	300	152.9	454.7	46.0	76.2	A				1217.2	293.0	1406.3
END8D9	300	150.9	451.8	46.6	77.3	A				1238.7	293.0	1453.3
END8E0	400	140.1	449.8	46.0	77.6	A				1121.1	294.0	1466.1
END8E1	400	135.2	446.9	44.8	76.4	A				1069.2	291.1	1415.1
END8E3	450	131.3	443.0	45.7	72.7	A				1110.3	307.7	1272.0
END8E5	500	127.4	428.3	45.3	75.8	A				1029.0	298.9	1390.6
END8E4	500	125.4	431.2	45.5	73.6	A				1028.0	311.6	1305.4
END8E6	550	126.4	414.5	48.0	75.3	A				1010.4	300.9	1370.0
END8E7	550	128.4	420.4	46.5	72.1	A				1007.4	301.8	1251.5
END8E8	600	129.4	394.0	48.7	72.9	A				961.4	293.0	1279.9
END8E9	600	126.4	393.0	47.0	74.4	A				1035.2	302.8	1335.7
END8F0	650	126.4	358.7	50.5	74.1	A				859.5	279.3	1324.0
END8F1	650	131.3	358.7	51.6	73.4	A				853.6	282.2	1297.5
END8F2	700	128.4	310.7	65.7	76.5	A				778.1	240.1	1419.0
END8F5	750	112.7	255.8	70.4	82.4	A				616.4	209.7	1702.3

Appendix2.1-8 Tensile test data







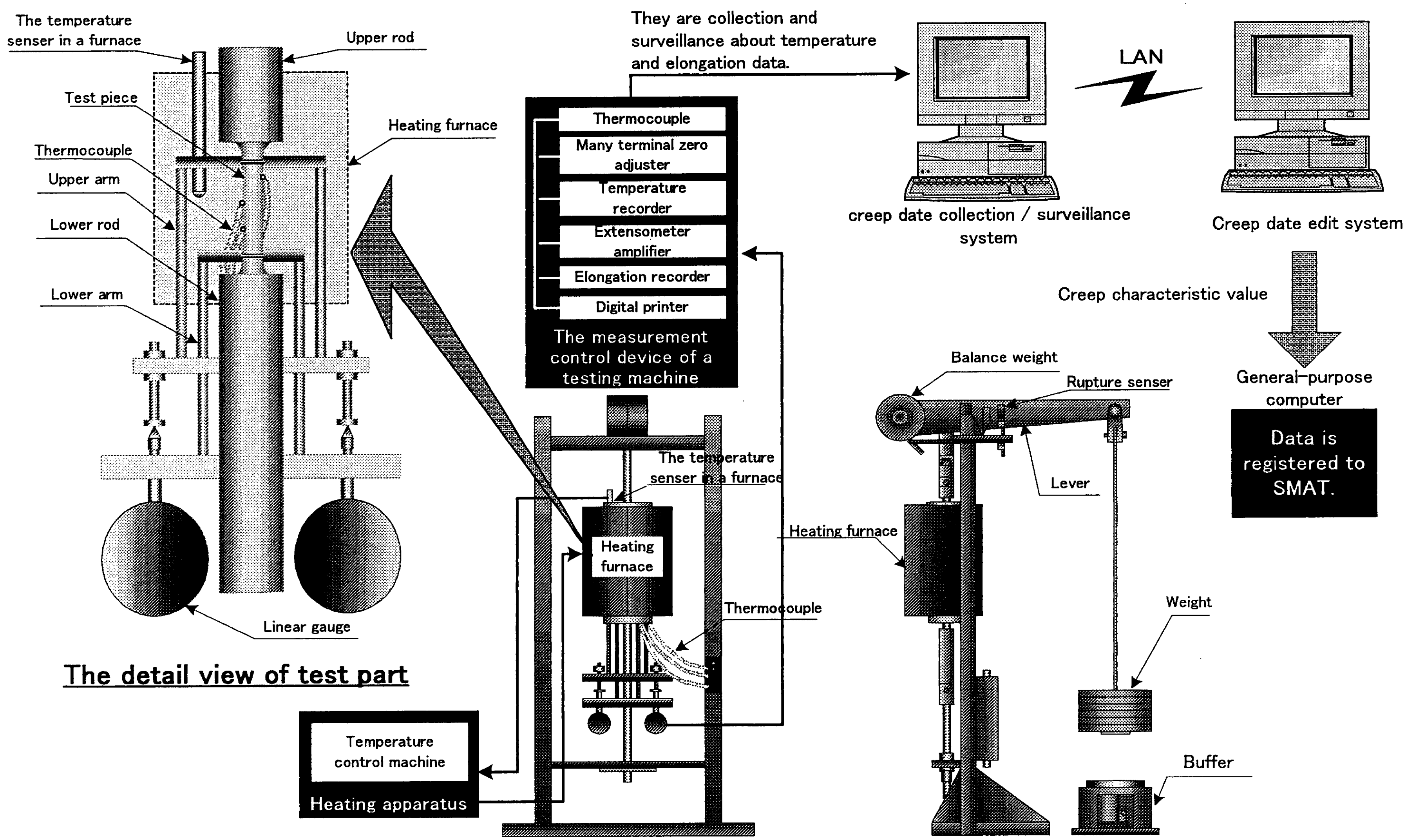
Appendix 2.1-9 Test data-processing system of structure materials test (SMAT)

Appendix2.2 Creep test

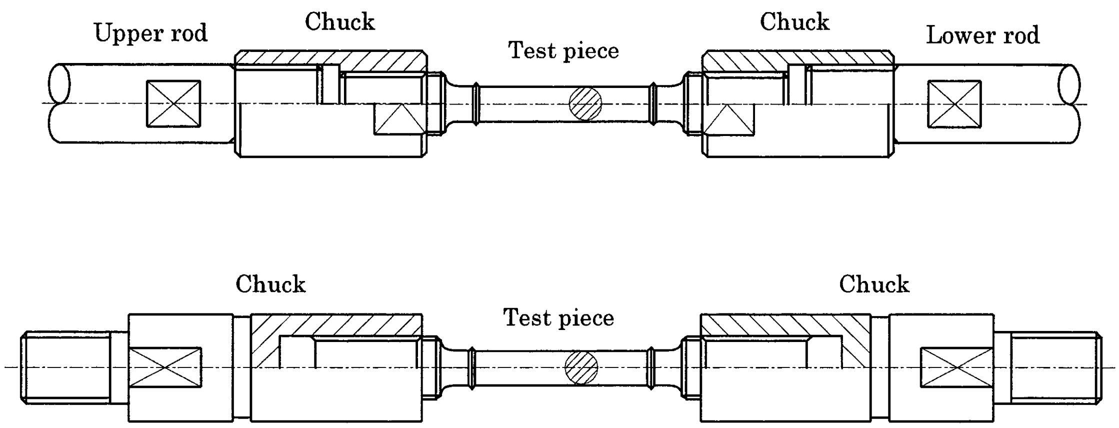
Appendix2.2-1 Specifications for creep test apparatus
Appendix2.2-2 Configuration figure of the creep test apparatus in the air
Appendix2.2-3 Configuration of the grip part of test piece for creep test
Appendix2.2-4 Online data collection system for creep test apparatus
Appendix2.2-5 FBR metal mechanical-test data sheet (creep)
Appendix2.2-6 Creep test data (Graph)
Appendix2.2-7 Creep test data (Graph)

Appendix2.2-1 Specifications for creep test apparatus

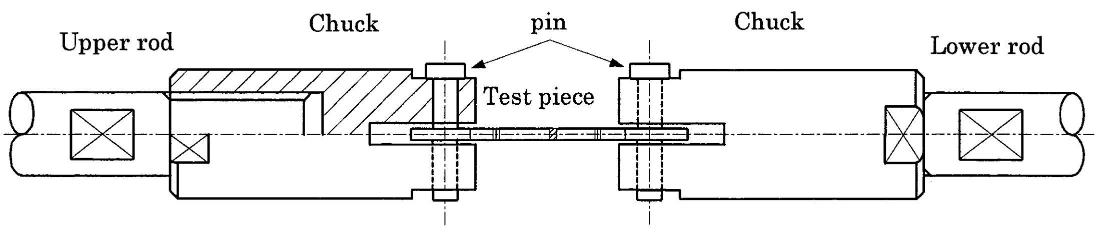
Name of test equipment		Vertical Double Lever Loading System	Vertical Single Lever Loading System			
Main test unit	1) Maximum load capacity	5000kg	750kg	3000kg		1500kg
	2) Lever ratio	1:40	1:10			
	3) Initial load	100kg	0kg			
Instrument for measuring elongation	1) Type	Displacement measurement system between collars of test piece				
	2) Sensor	Linear gauge & dial gauge			DTF&dial gauge	
	3) Measurement area	0～20mm				
	4) Measurement range	20,10,5,2mm/F.S accuracy 0.5%/F.S				
Heating device	1) Type	Half pipe-type electric furnace				
	2) Capacity	3KW				
	3) Temperature range control	300～1000℃				
	4) Control method	PID control method				
Number of test machines		5	5	36	30	15



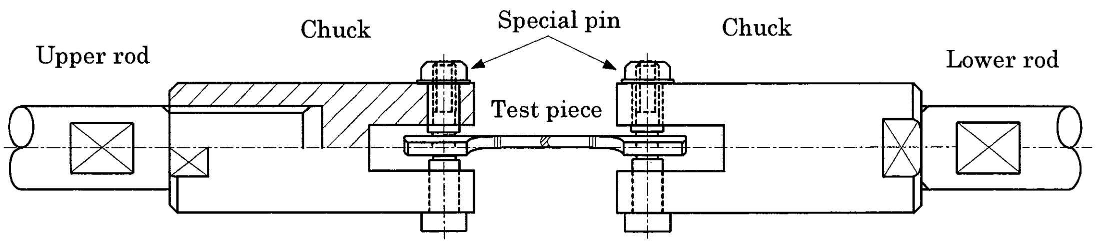
Appendix 2.2-2 Configuration figure of the creep-test apparatus in the air



The chuck attachment figure for bar form test piese

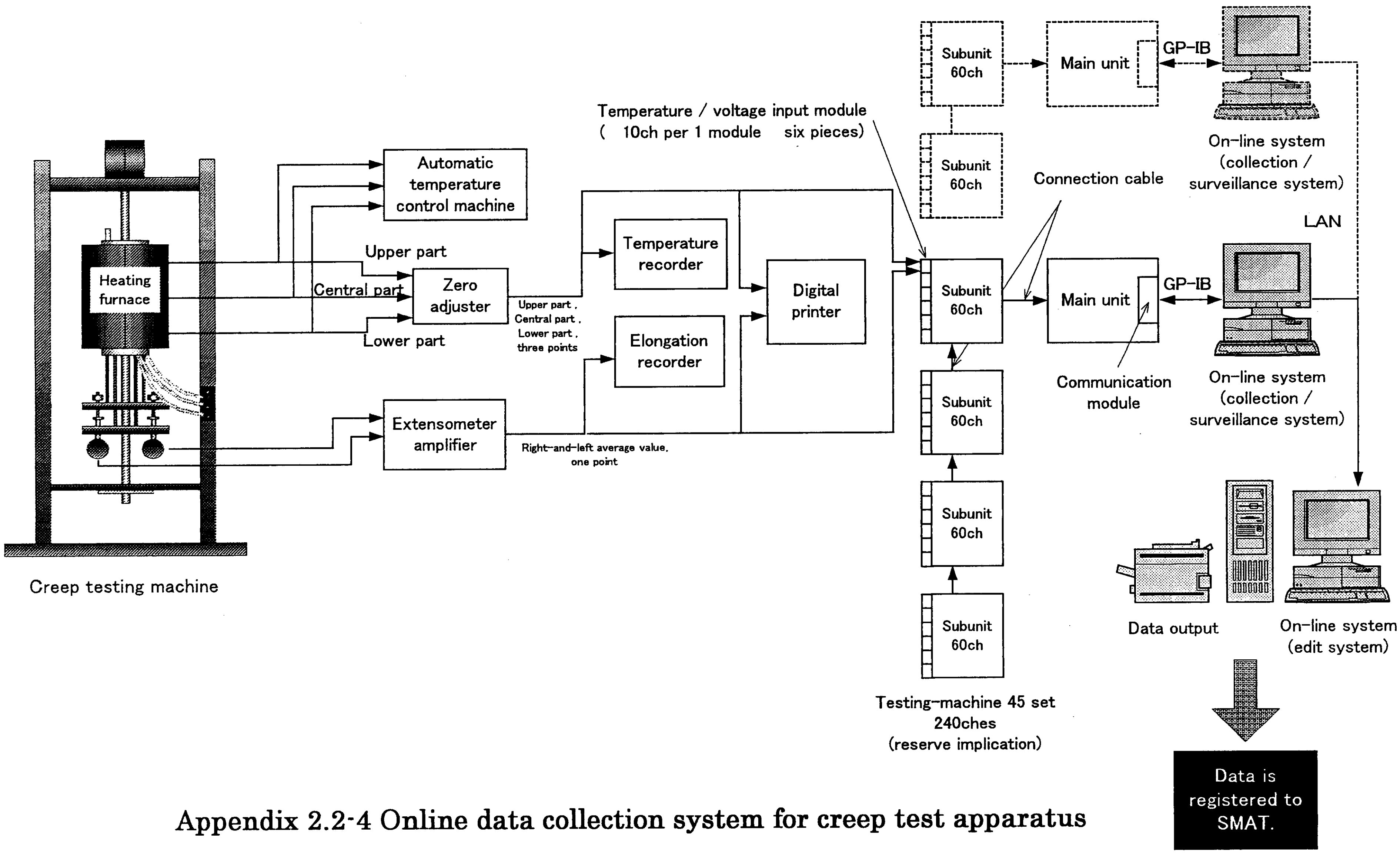


The chuck attachment figure for flat form test piese



The chuck attachment figure for arc section test piese

Appendix2.2-3 Configuration of the grip part of test piece for creep test

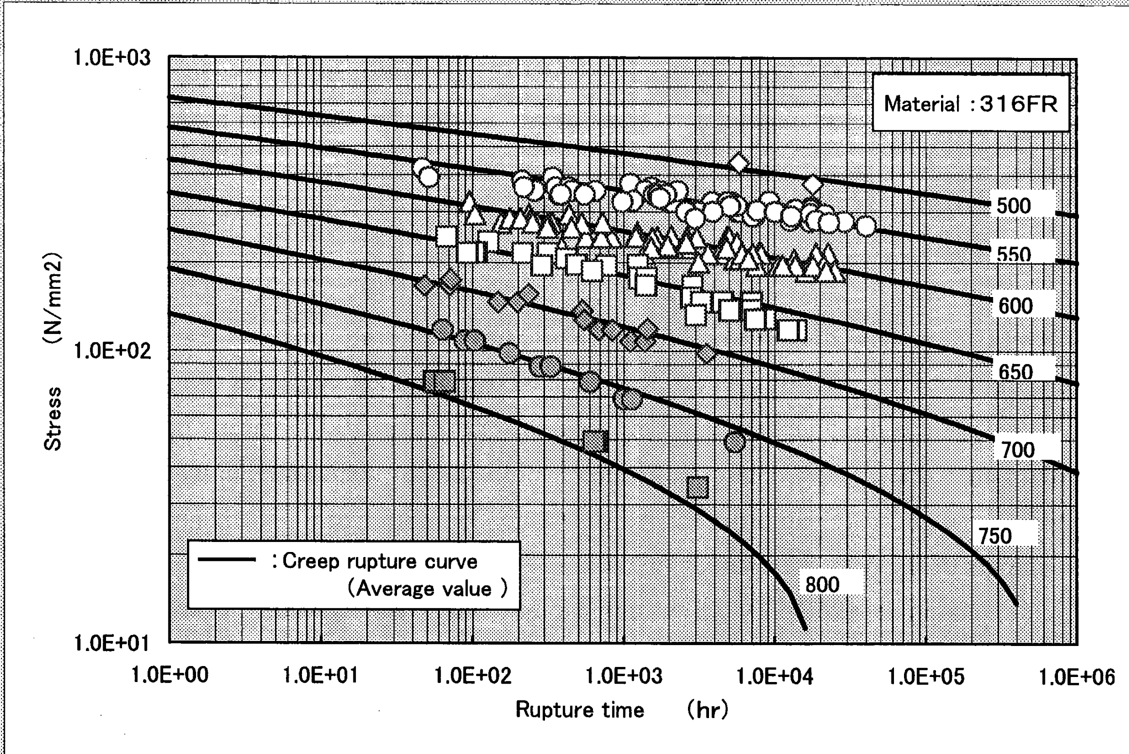


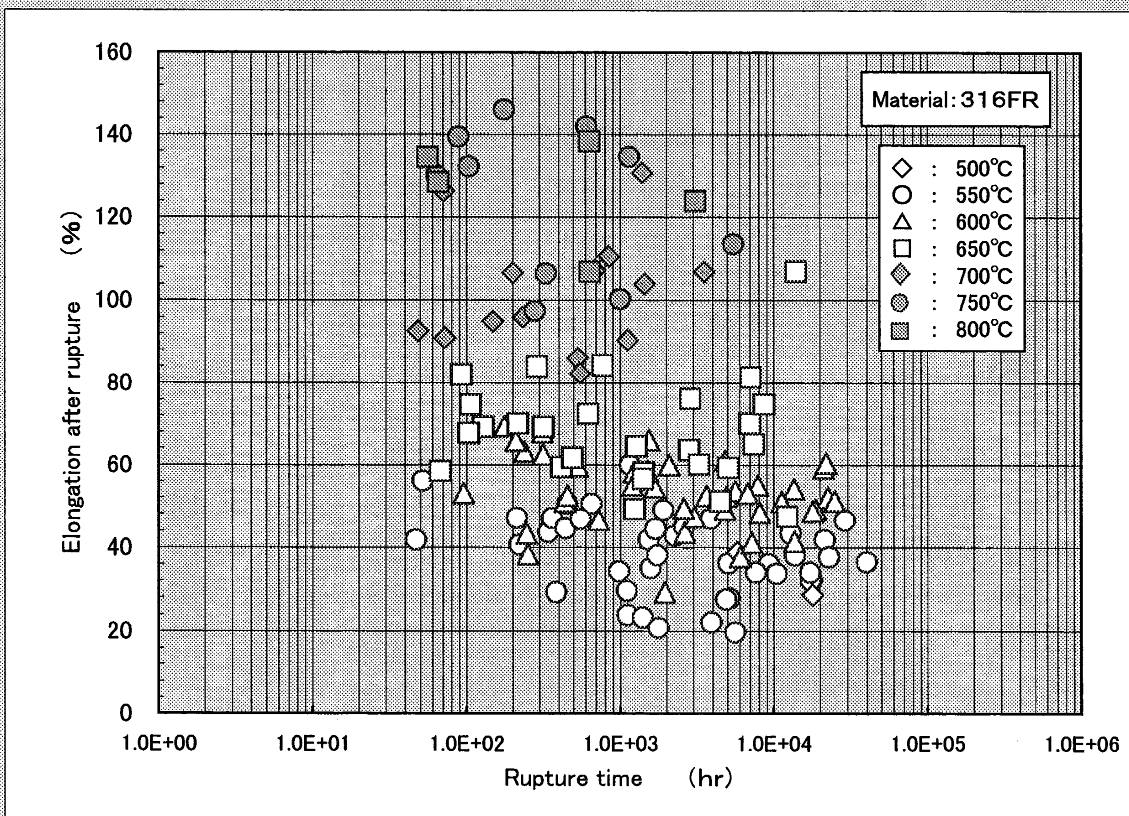
Appendix 2.2-4 Online data collection system for creep test apparatus

Appendix2.2-5 FBR metallic materials test data sheet (creep)

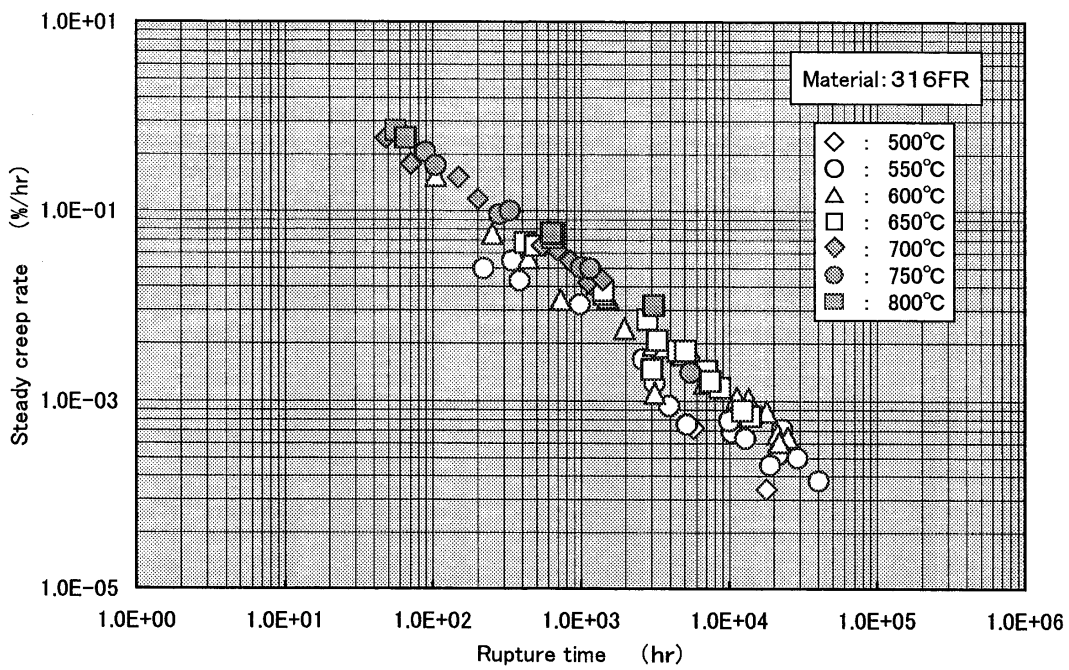
Test condition	Air														
Test piece No	Test temperature (°C)	Initial stress (N/mm²)	Rupture time (hr)	Elongation after rupture (%)	Reduction of area (%)	Ruputure position	Steady c reep rate (%/hr)	Time to load completion (min)	Strain on load (%)	Primary creep	Secondary creep		Tertiary creep		The number of times of discontinuation of test
										Strain(%)	Start time (hr)	Strain(%)	Start time (hr)	Strain(%)	
FMF8B4	500	372.6	17842.1	28.7	35.6	B	1.15E-04	6.0	17.457	0.151	440.0	1.359	10100.0	9.033	0
FN0BA0	550	323.6	3403.8	41.1	54.5	B	1.97E-03	4.0	12.662	0.715	350.0	2.979	1410.0	26.318	0
FNF8C4	550	300.1	10418.9	33.6	43.3	A	4.69E-04	5.0	11.162	0.503	560.0	2.278	4420.0	19.657	1
FNF8C0	550	277.5	29027.4	46.5	44.7	A	2.50E-04	5.0	8.432	0.592	1020.0	2.609	9638.0	34.867	2
FNF8C3	550	267.7	40303.2	36.5	41.2	B	1.42E-04	4.0	8.927	0.292	1650.6	1.912	12053.1	34.331	1
FNF8B2	600	274.6	726.2	46.6	67.7	A	1.15E-02	3.0	10.628	0.233	20.0	2.506	200.0	33.233	0
FNF8B3	600	225.6	4810.3	61.0	61.0	A	3.09E-03	2.0	5.353	1.036	180.0	4.402	1360.0	50.209	0
FNF8B4	600	205.9	13423.9	54.1	62.0	B	1.05E-03	3.0	4.760	0.489	580.0	6.049	5570.0	42.802	1
FNF8C5	600	188.3	24832.6	51.1	64.7	A	4.15E-04	3.0	3.217	1.078	3535.0	5.322	12339.0	41.483	1
FNF8B5	650	166.7	1416.1	56.4	73.2	B	1.43E-02	2.0	2.383	0.547	69.0	7.915	541.0	45.155	0
FNF8B6	650	137.3	7092.7	81.3	73.7	A	2.05E-03	2.0	1.220	0.710	390.0	4.977	2330.0	74.393	0
FNF8B7	650	117.7	13909.2	107.0	70.8	B	6.87E-04	2.0	0.253	0.467	800.0	2.331	3100.0	103.949	1
FNF8A8	700	166.7	70.7	126.3	80.6	A	3.18E-01	3.0	2.862	0.582	4.0	4.783	14.4	118.073	1
FNF8A9	700	147.1	199.8	106.7	80.4	A	1.35E-01	3.0	1.716	0.387	4.0	6.946	50.0	97.651	0
FNF8B0	700	117.7	843.9	110.7	79.5	A	2.99E-02	3.0	0.248	0.358	50.0	5.905	190.0	104.189	0
FNF8B1	700	107.9	1390.4	130.7	78.4	A	1.87E-02	2.0	0.169	0.124	30.0	8.254	430.0	121.632	0
FNF8A0	750	107.9	104.4	132.2	85.3	A	3.08E-01	2.0	0.250	0.148	2.0	8.523	27.0	123.279	1
FNF8A1	750	88.3	331.8	106.5	88.9	B	1.01E-01	1.0	0.111	0.238	10.0	6.858	66.0	99.293	0
FNF8A6	750	68.6	1147.5	134.6	83.3	A	2.46E-02	1.0	0.091	0.128	12.0	7.585	300.0	126.796	0
FNF8A7	750	49.0	5461.1	113.5	72.3	A	2.01E-03	1.0	0.018	0.061	30.0	1.007	405.0	112.414	0
FNF8A3	800	78.5	65.9	128.4	91.5	B	5.93E-01	1.0	0.095		1.0		20.8		0
FNF8A4	800	49.0	636.1	138.2	85.4	B	5.78E-02	2.0	0.042	0.416	80.0	17.933	307.0	119.809	1
FNF8A5	800	34.3	3102.3	123.9	71.3	A	1.00E-02	2.0	0.044	0.279	230.0	13.301	1310.0	110.276	0

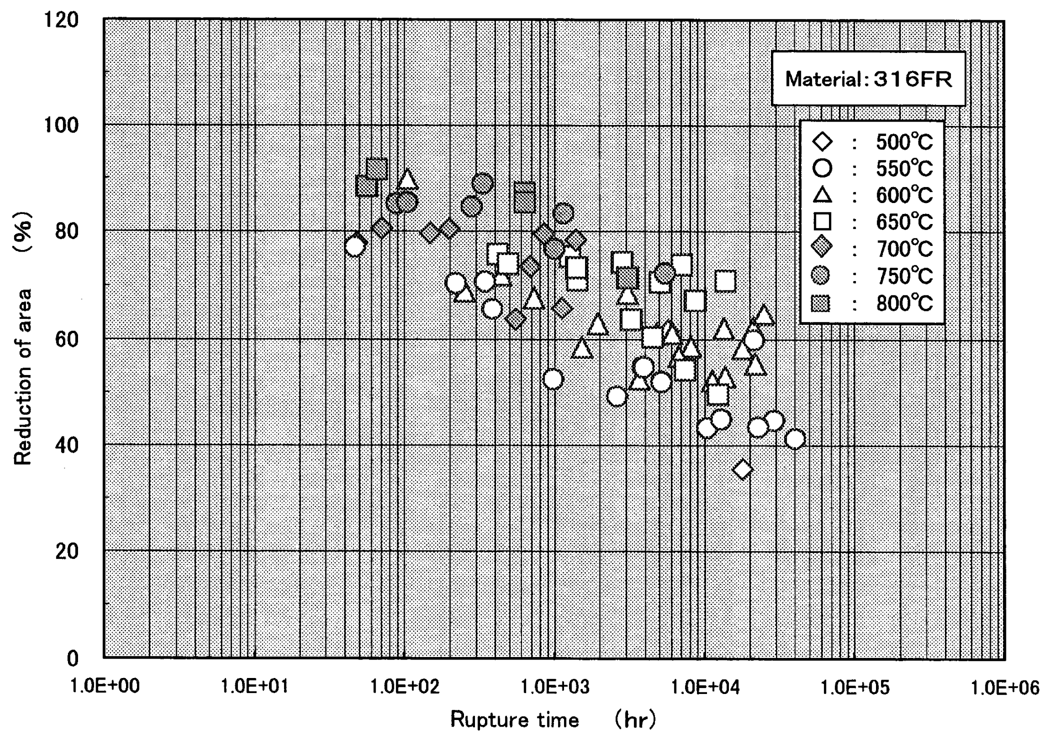
Appendix 2.2-6 Creep test data





Appendix2.2-7 Creep test data



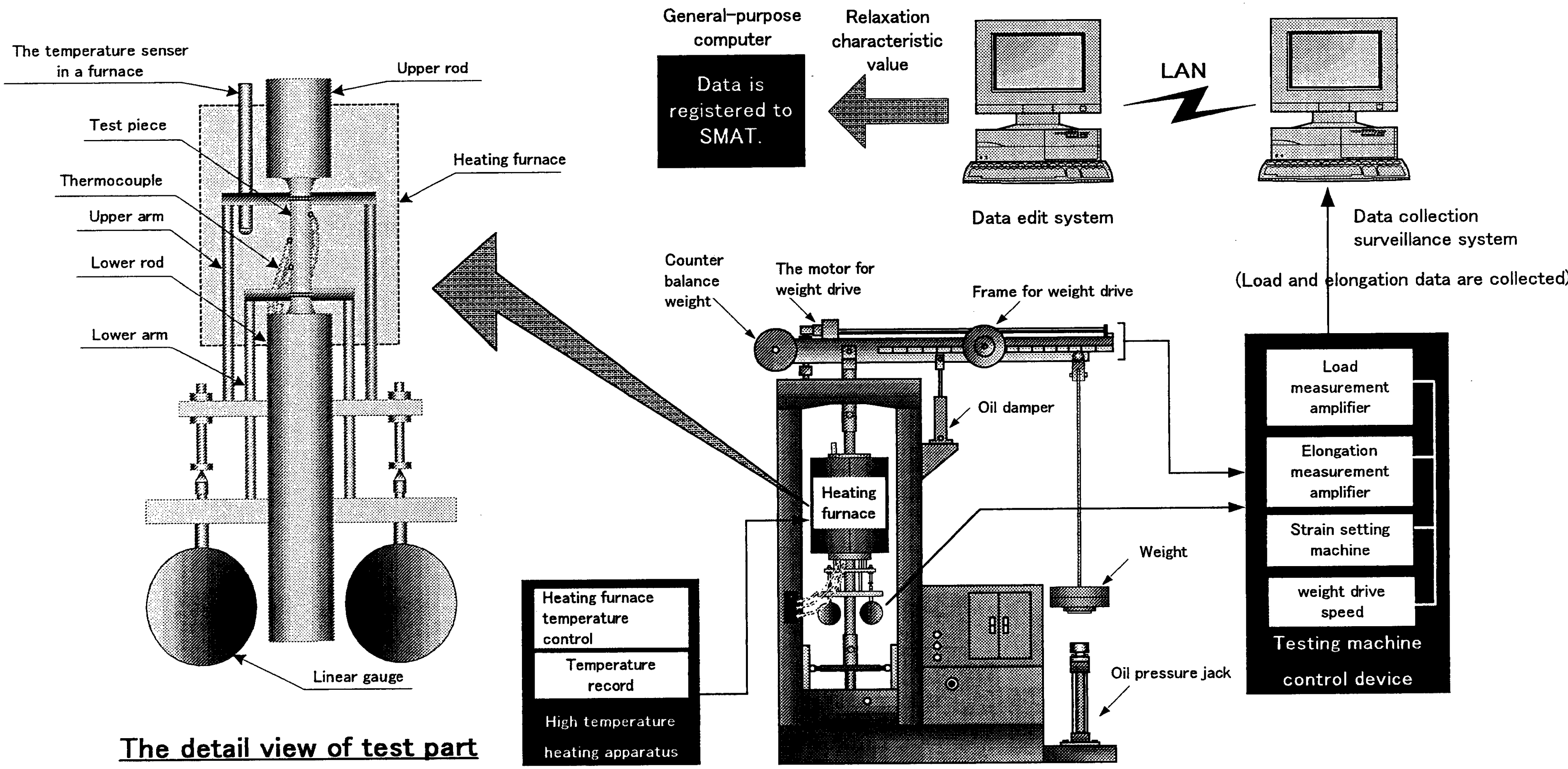


Appendix2.3 Relaxation test

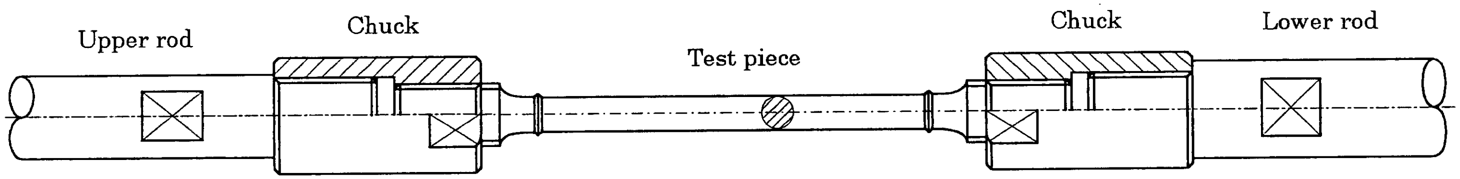
Appendix2.3-1	Specifications for relaxation test apparatus
Appendix2.3-2	Configuration of a relaxation test apparatus
Appendix2.3-3	Configuration of the grip part of a relaxation test piece
Appendix2.3-4	Online data collection system for relaxation test
Appendix2.3-5	FBR metallic materials test data sheet (relaxation)
Appendix2.3-6	Relaxation test date (Graph)

Appendix2.3-1　Specifications for relaxation test apparatus

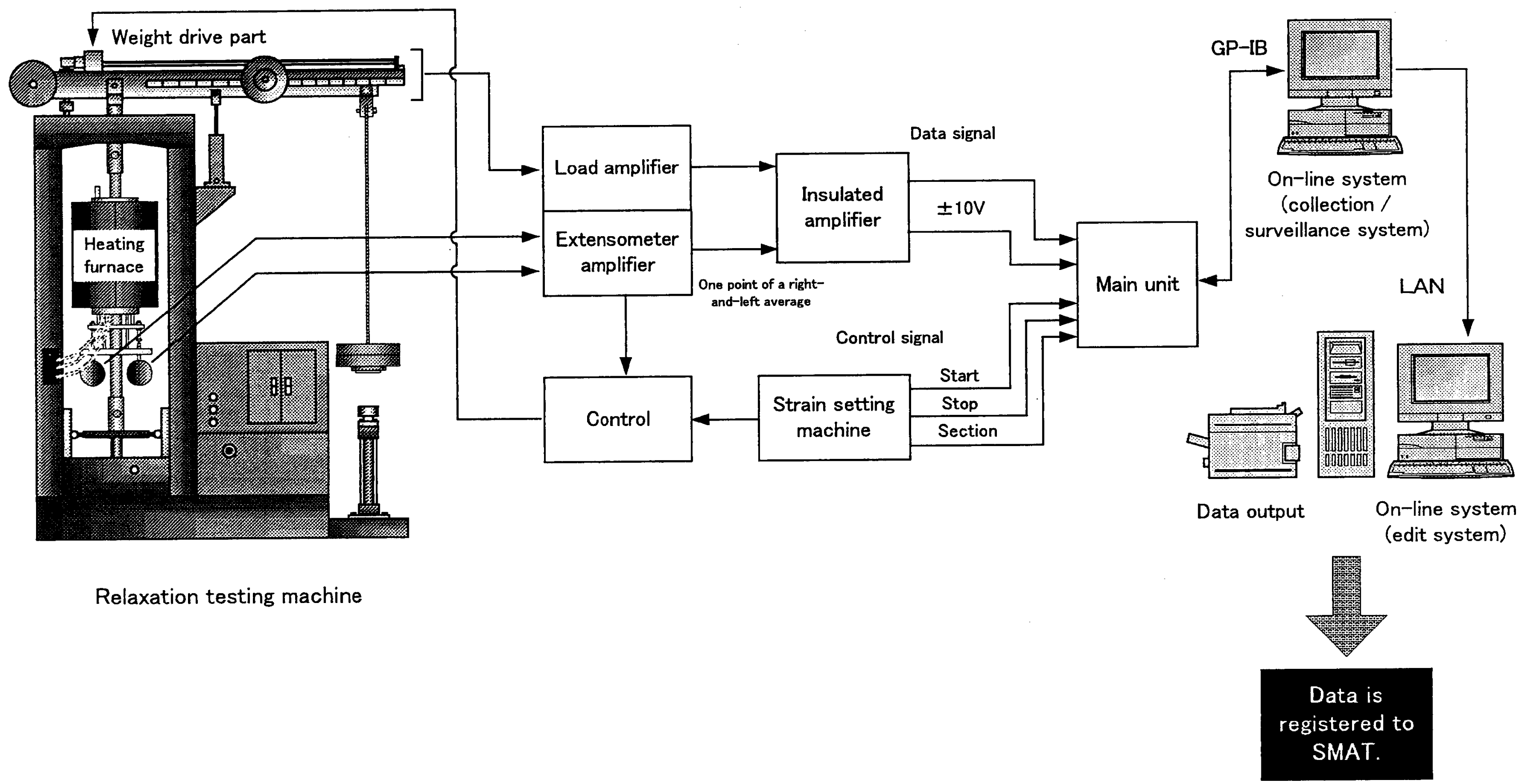
Specifications \ Test machine No.	AR－1, 2
1. Main Testing Machine	
(1) Type	Vertical single Lever Loading System　RX－30 type
(2) Maximum load capacity	3000kg
(3) Lever ratio	1：20
(4) Load accuracy	±0.5%
(5) Moving speed of relaxation weight	Max. 130 sec./ full stroke
2. Elongation measuring device	
(1) Type	Detect the elongation between gauge lengths and maintain the elongation constant by adjusting the relaxation weight.
(2) Elongation sensor	Digital linear gauge
(3) Sensitivity	0.5 μ or less
(4) Strain adjuster	Setting range　0～3 mm
3. Heating device	
(1) Type	Half pipe-type electric furnace
(2) Capacity	3 KW
(3) Controlled temperature range	200℃～800℃
(4) Control method	PID control method



Appendix 2.3-2 Configuration of relaxation test apparatus



Appendix 2.3-3 Configuration of the grip part of relaxation test piece

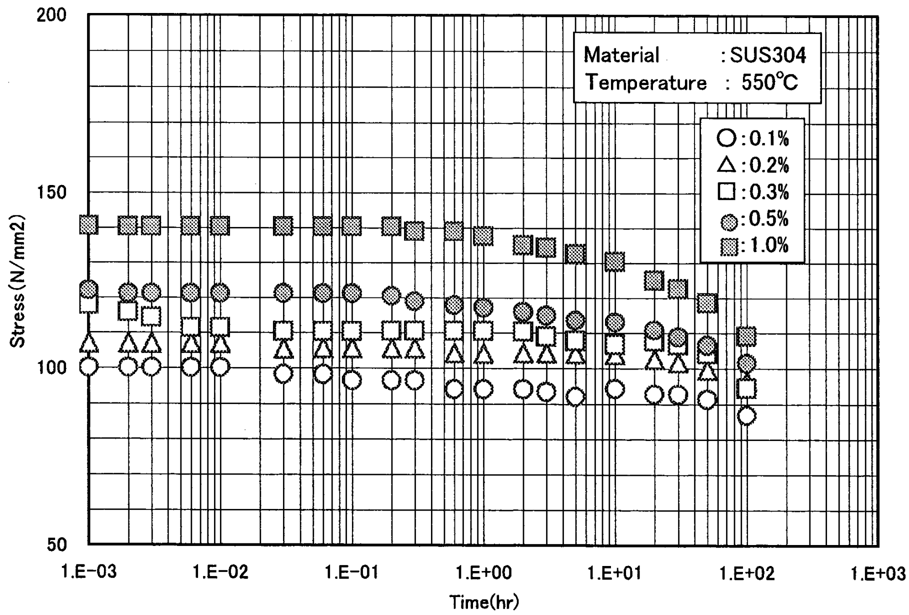


Appendix 2.3-4 On-line data collection system for relaxation test

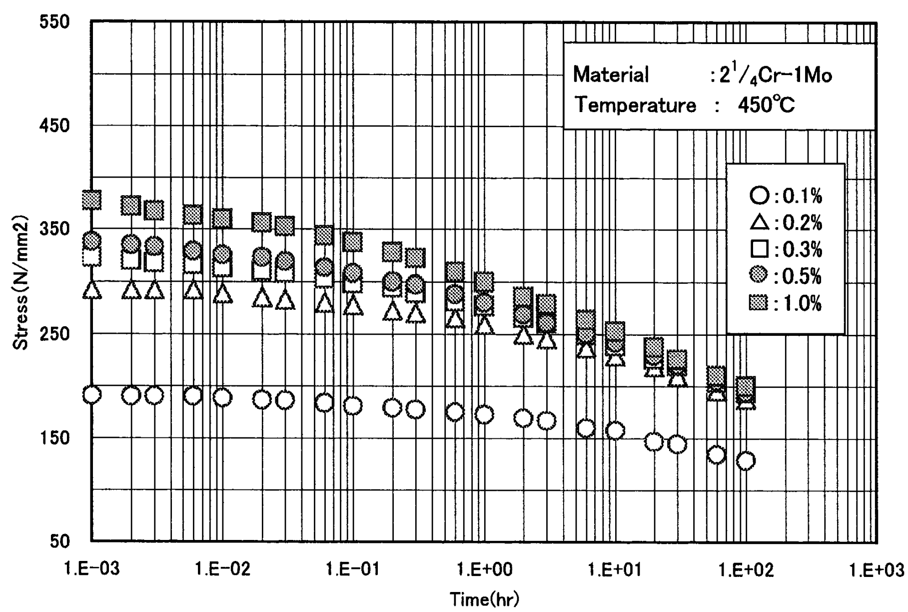
Appendix2.3-5 FBR metallic materials test data sheet (relaxation)

Test condition	In air						
Test piece No	Test temperature (°C)	Total strain (%)	Stress on load (N/mm^2)	Time to load completion (min)	Load holding time (sec)	Test time (hr)	The last residual stress (N/mm^2)
ABR107	550	0.1	102.0	3.10	13	100	86.8
ABR108	550	0.2	110.3	3.10	15	100	96.4
ABR102	550	0.3	119.9	3.33	7.5	100	94.5
ABR103	550	0.5	123.0	3.33	7	100	101.4
ABR106	550	1.0	140.6	3.55	15	100	109.1
GCG3A8	450	0.1	192.9	3.10	30	100	128.8
GCG3C4	450	0.2	295.5	3.10	23	100	187.6
GCG3B4	450	0.3	326.4	3.33	30	100	193.5
GCG3C0	450	0.5	348.1	3.33	28	100	194.3
GCG3C7	450	1.0	388.8	3.55	30	100	200.2

Appendix 2.3-6 Relaxation test data



The stress relaxation curve in 550 ℃ of SUS304 steel



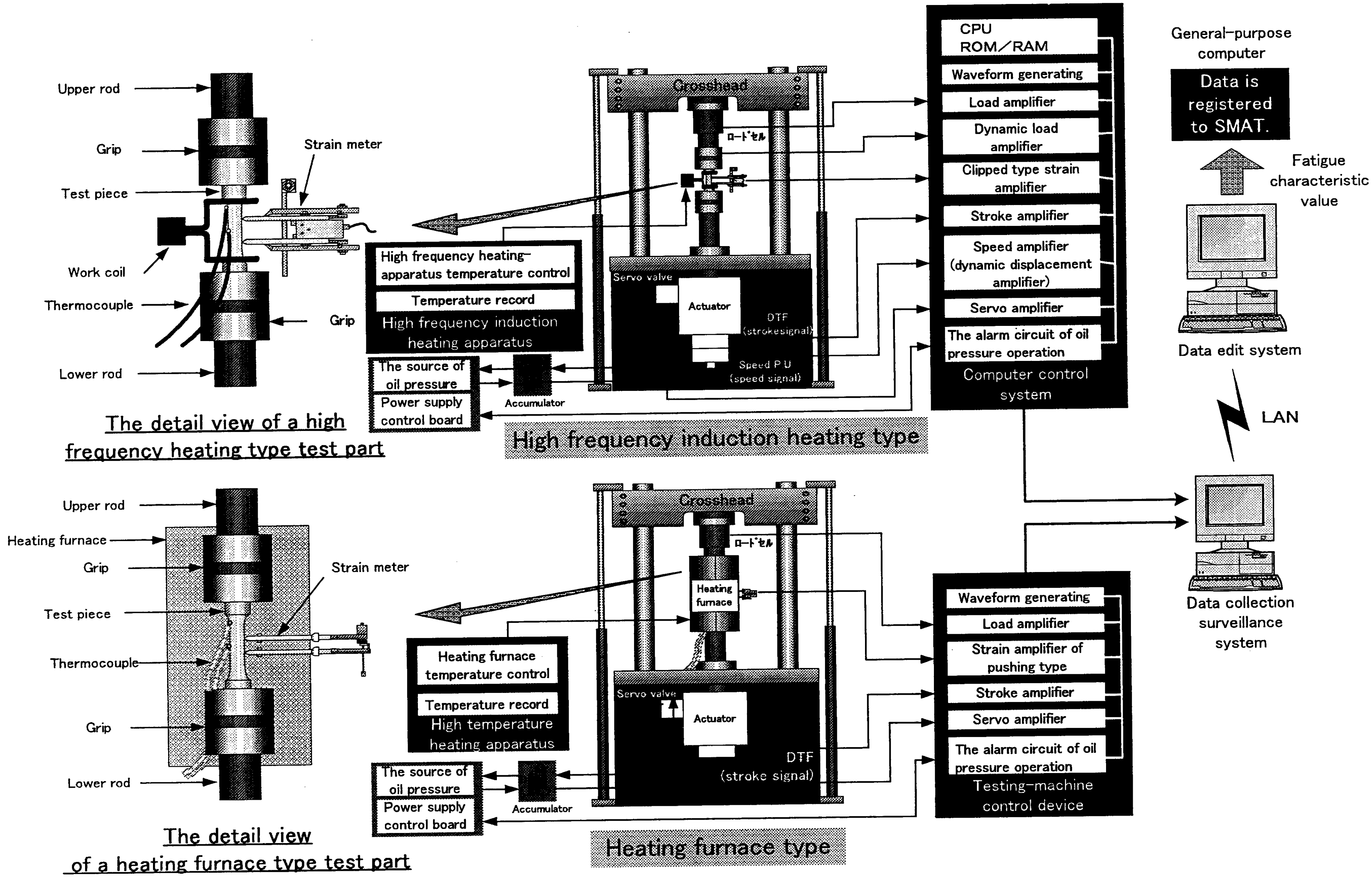
The stress relaxation curve in 450 ℃ of $2^1/_4$Cr-1Mo steel

Appendix2.4 Low cycle fatigue test

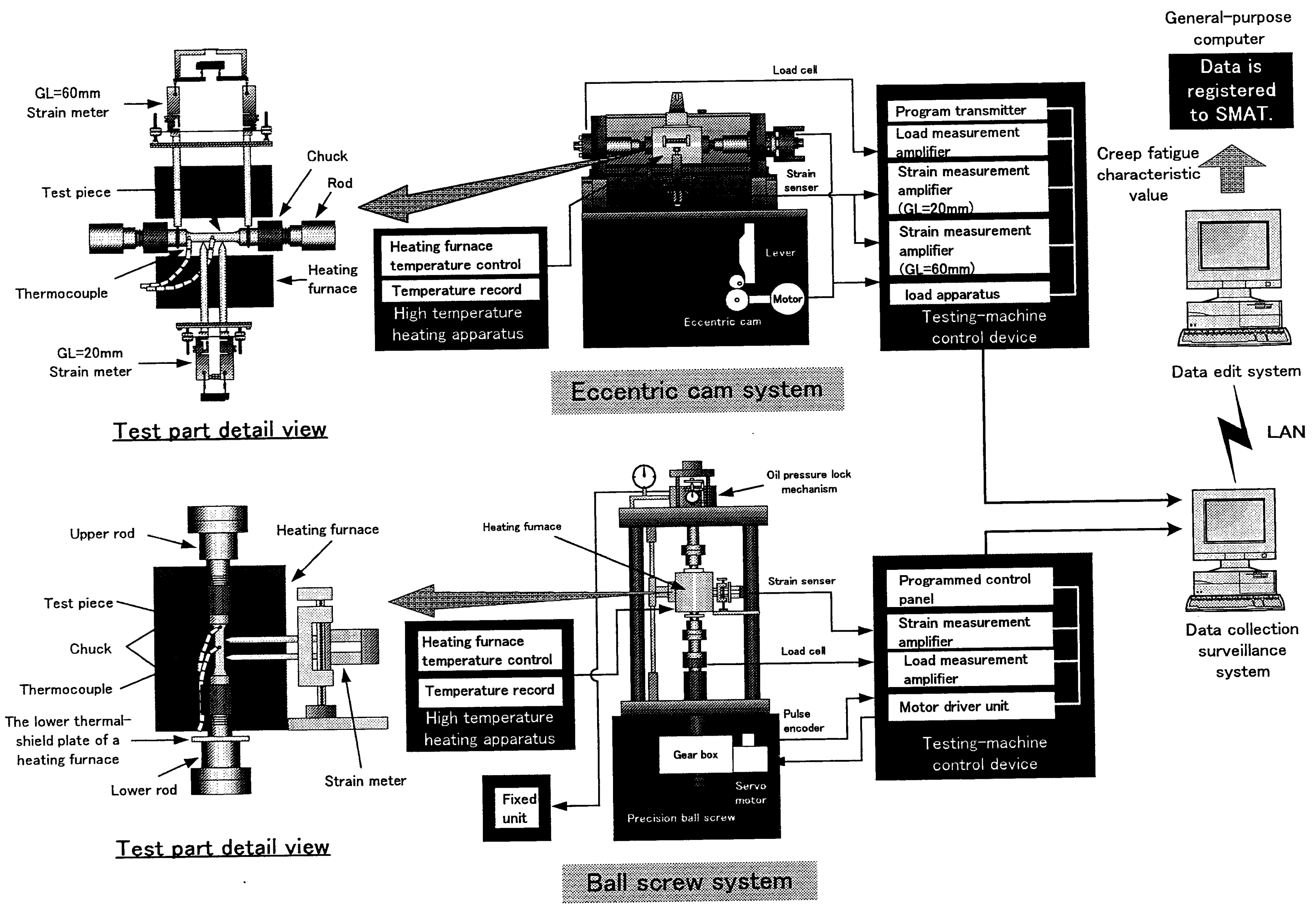
Appendix2.4-1 Specifications for fatigue test apparatus
Appendix2.4-2 Configuration of an electric hydraulic-servo control system fatigue test apparatus
Appendix2.4-3 Configuration of electric servo motor control system Fatigue test apparatus
Appendix2.4-4 Configuration of the grip part of test piece for fatigue test (hydraulic-servo type)
Appendix2.4-5 Configuration of the grip part of test piece for creep fatigue test for a long time (Electric servo motor type)
Appendix2.4-6 Appearance figure of the strain meter for fatigue test (hydraulic-servo type)
Appendix2.4-7 Configuration of the strain meter for fatigue test (electric servo motor formula)
Appendix2.4-8 Configuration of the strain meter for fatigue test in sodium (hydraulic-servo type)
Appendix2.4-9 Online data collection system for fatigue test
Appendix2.4-10 Preparation and adjustment of a work coil
Appendix2.4-11 FBR metallic materials test data sheet (fatigue)
Appendix2.4-12 Example of representation of hysterisis loop
Appendix2.4-13 Low cycle fatigue-test data (Graph)
Appendix2.4-14 Prolonged creep-fatigue-test data (Graph)
Appendix2.4-15 Calibration of strain in fatigue test in sodium

Appendix2.4-1 Specifications for fatigue test apparatus

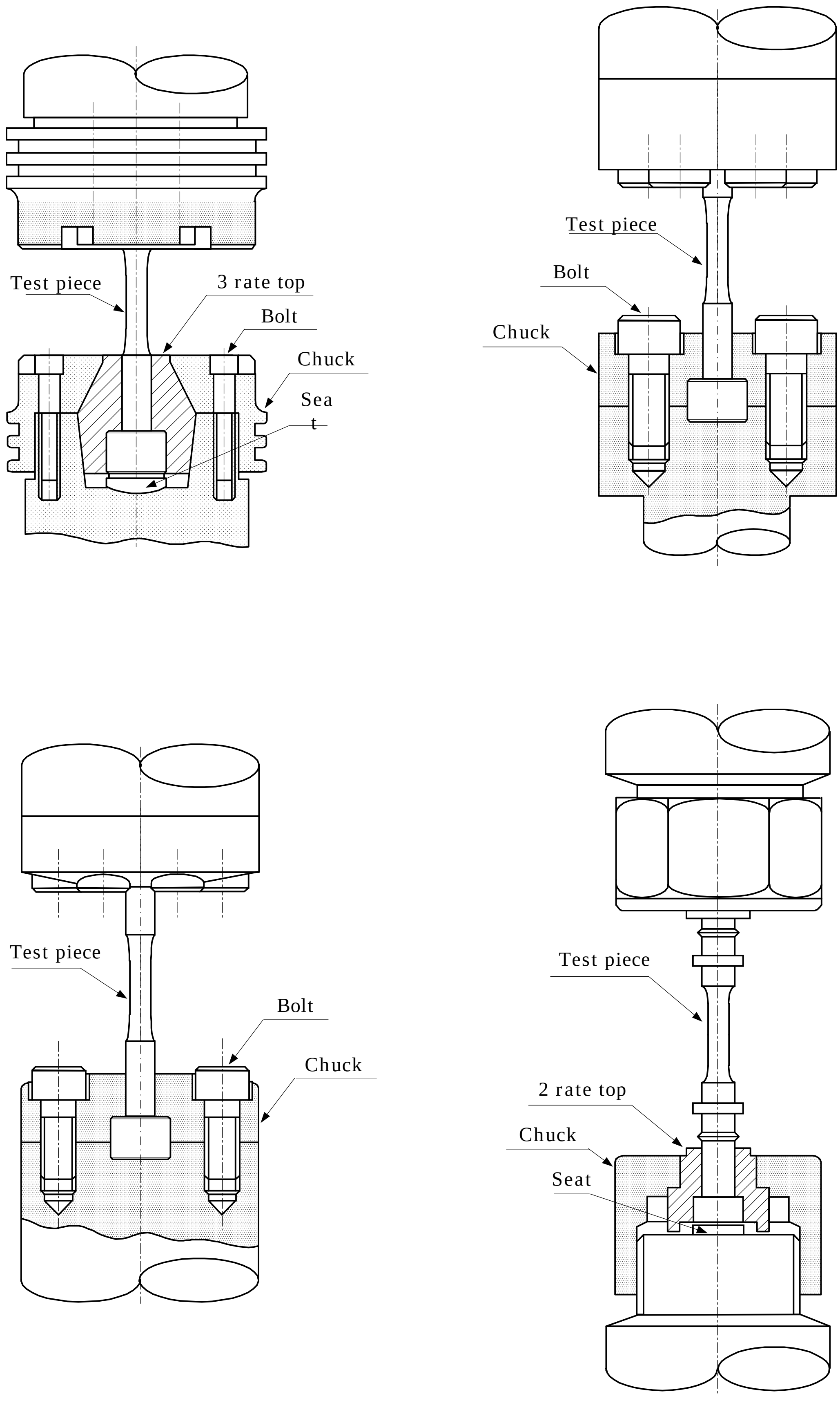
	Name of the testing equipment	Electric-Hydraulic Servo Control System			Electric Servo Motor Control Ball Screw System	Electric Servo Motor Control Eccentric Cam System
	Test atmosphere	Atmospheric air		In Na & atmospheric air	Atmospheric air	Atmospheric air
Repeated Loading Instrument	1) Maximum load	Dynamic ±10.0ton		Dynamic ±10.0ton	Dynamic ±5.0ton	Dynamic ±5.0ton
	2) Maximum stroke	±50mm		±50mm	±50mm	±3mm
	3) Load cell	±10.0t accuracy 1.0%F.S		±10.0t accuracy 0.5%F.S	±5.0t accuracy 0.5%F.S	±5.0t accuracy 0.5%F.S
	4) Control method	Load, strain, stroke		Load, strain, stroke	Load, strain	Load, strain
	5) Controlled waveform	Sine wave, ramp wave, square wave		Sine wave, ramp wave, square wave	Ramp wave	Ramp wave
	6) Loading rate	10^{-6}Hz～10Hz		10^{-6}Hz～10Hz	10^{-5}Hz～10^{-4}Hz	10^{-5}Hz～10^{-4}Hz
	7) Test piece type	Button type		Button type	Button type	Screw type
Instrument for measuring strain	1) Type	Quartz rod push method		Arm shoulder method Quartz rod push method	Quartz rod push method	Quartz rod push method
	2) Measurement range	±1.0mm accuracy 1%F.S		±1.0mm accuracy 1%F.S ±1.0mm accuracy 1%F.S	±0.5mm accuracy 1%F.S	±1.0mm accuracy 1%F.S
	3) Sensor	Strain gauge, LVDT		LVDT	Strain gauge	Strain gauge
Heating device	1) Type	High-frequency induction heating system	Half pipe-type electric furnace	Half pipe-type electric furnace	Half pipe-type electric furnace	Half pipe-type electric furnace
	2) Maximum output	6～10KW	4.5KW	5KW	2.4KW	5KW
	3) Controlled temperature range	200℃～800℃	300℃～900℃	300℃～800℃	400℃～800℃	300℃～800℃
	4) Control method	PID control	PID control	PID control	PID control	PID control
Number of testing machines		5 units	4 units	2 units	4 units	2 units



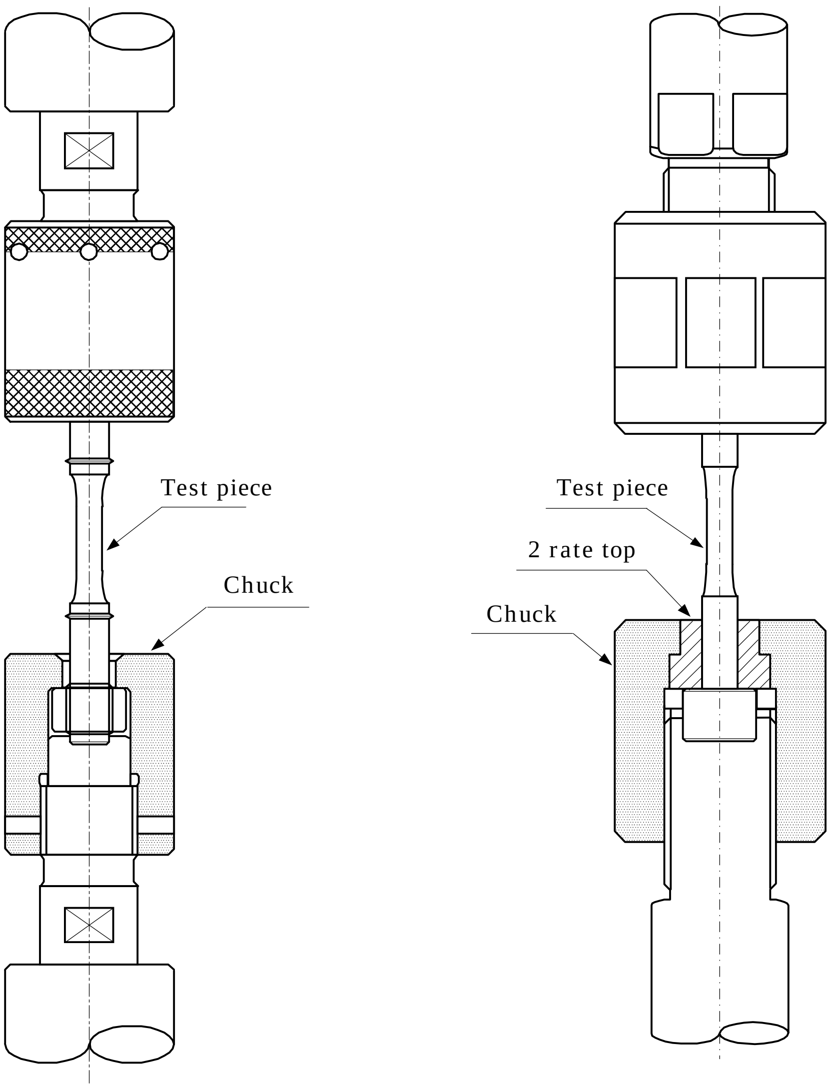
Appendix 2.4-2 Configuration of an electric hydraulic-servo control system fatigue test apparatus



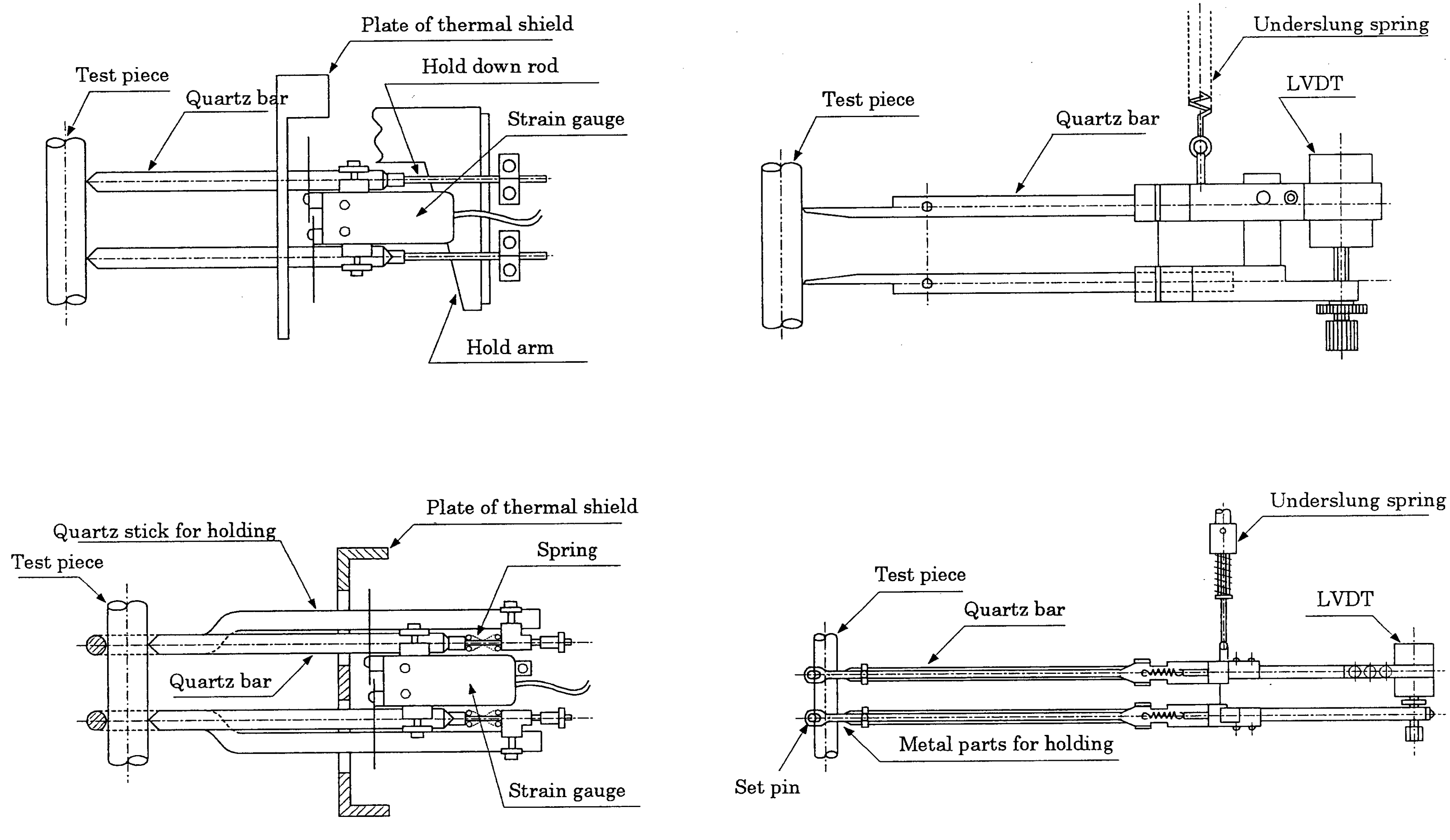
Appendix 2.4-3 Cofiguration of electric servo motor control system fatigue test apparatus



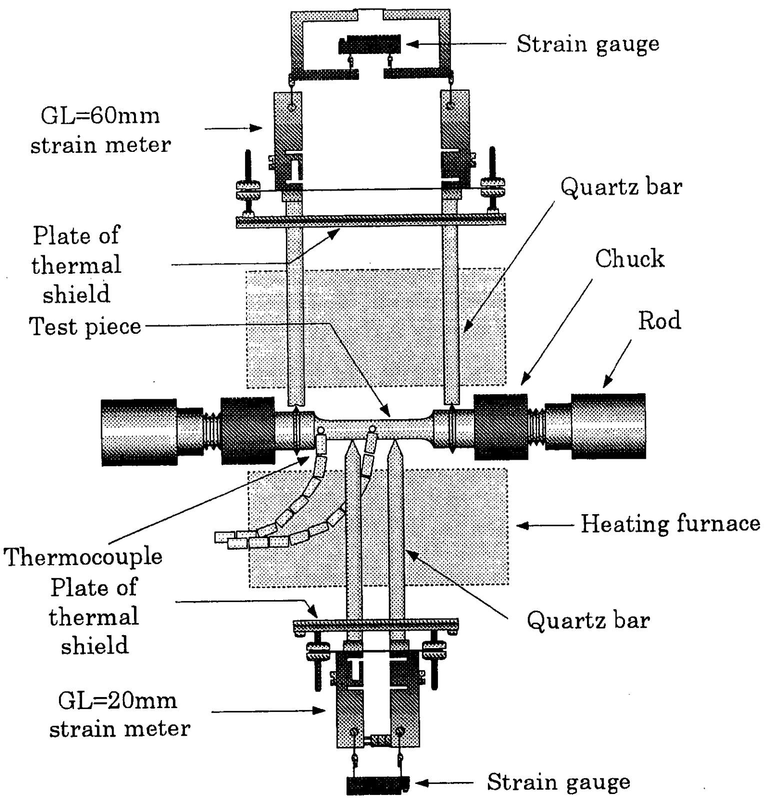
Appendix 2.4-4 Configuration of the grip part of test piece for fatigue test (hydraulic-servo type)

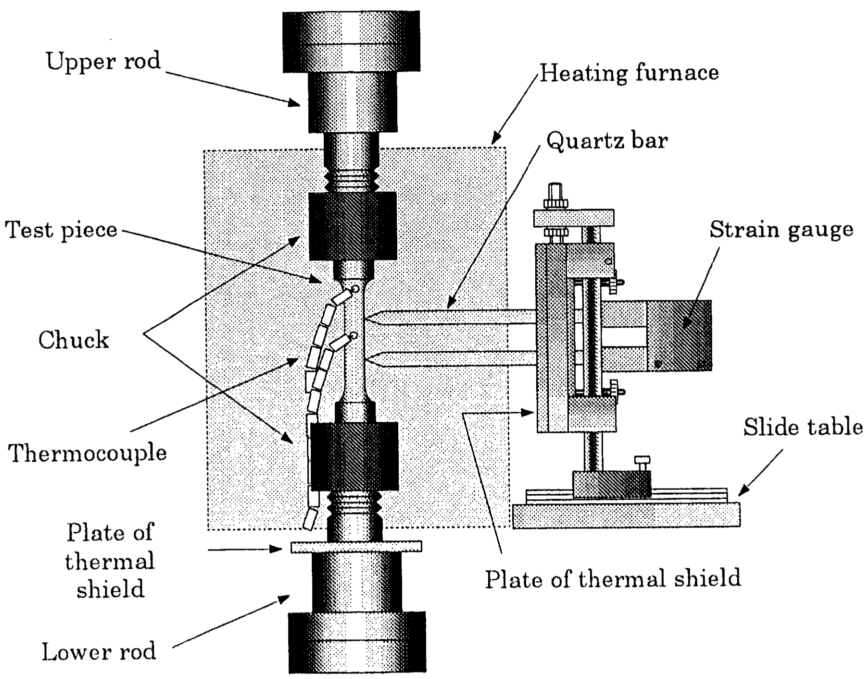


Appendix 2.4-5 Configuration of the grip part of test piece for creep fatigue test for a long time (Electric servo motor type)

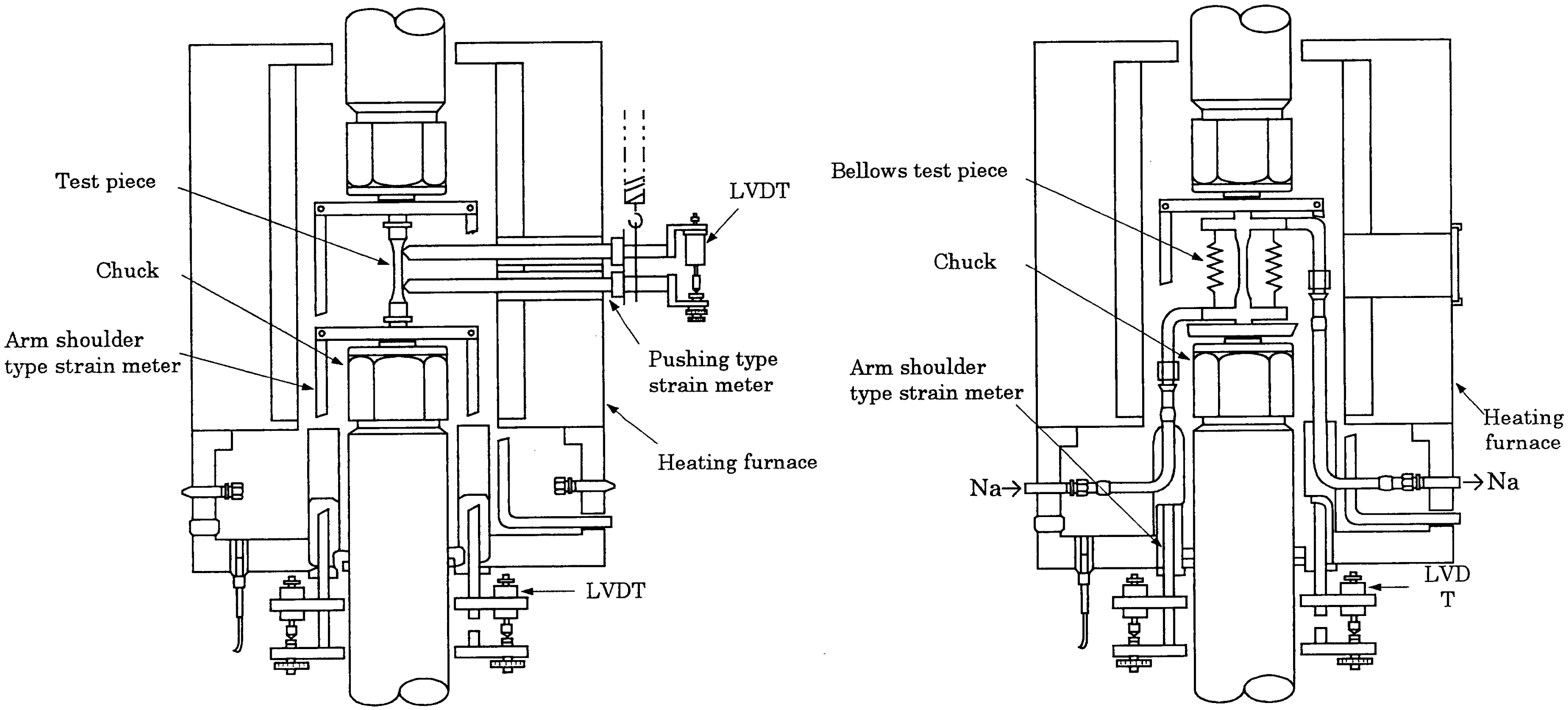


Appendix 2.4-6 Appearance figure of the strain meter for fatigue test (hydraulic-servo type)





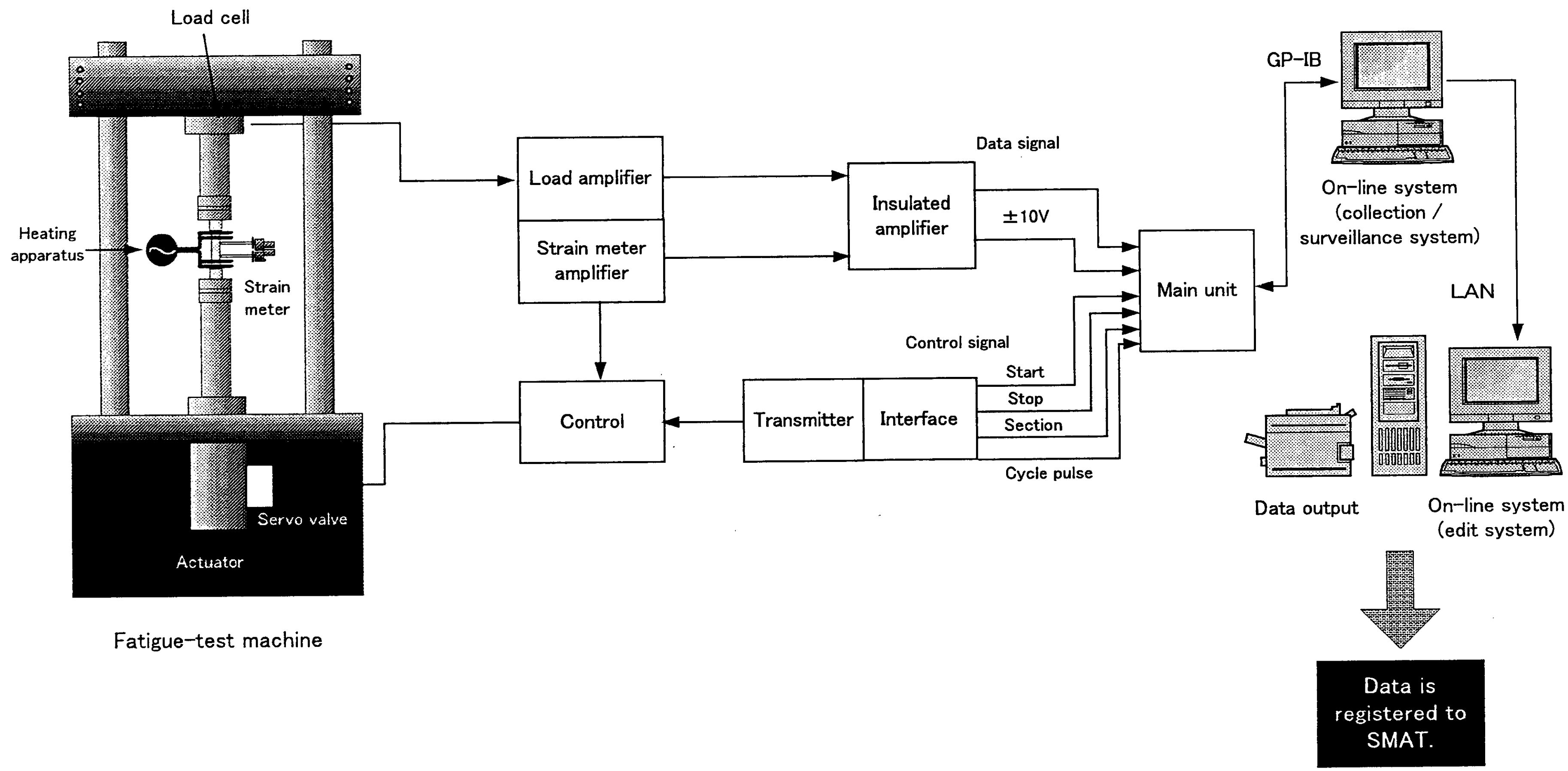
Appendix 2.4-7 Configuration of the strain meter for fatigue test (electric servo motor formula)



Test in air

Test in sodium

Appendix 2.4-8 Configuration of the strain meter for fatigue test in sodium (hydraulic-servo type)



Appendix 2.4-9 Online data collection system for fatigue test

Appendix2.4-10 Preparation and adjustment of a work coil

One method to heat a test piece and expose it to a high temperature for a long time during the fatigue test in atmospheric air is the high-frequency induction heating system. In this case, the number of coils and coil spacing of a work coil for heating must be adjusted so that the parallel portion of the test piece is uniformly heated and maintained at a specified temperature. Regarding the preparation of the work coil, the following points need to be considered:

- The distribution characteristics of the temperature of the parallel portion of the sample vary depending on the thermal conductivity of test materials and testing apparatus.

  〔In general, high frequency is used for materials with low thermal conductivity (stainless steel, etc), and a heating furnace is used for materials with high thermal conductivity (carbon steel, low-alloy steel, etc)〕

- The distribution characteristics of the temperature change according to the inside diameter of a work coil, and the diameter, number of coils, and direction the coils are wound around the copper pipes.

  〔By making the inside diameter of the coil small, and the diameter of pipe large, and by increasing the number of coils, the density of the magnetic field lines inside the coil will increase. Also, if the direction the coils are wound is the same for upward and downward, then the temperature at the center of the test piece will be high, while if the directions are opposite, the temperature will be low.〕

After considering the above, a work coil should be prepared by using the following procedure (refer to attached figure 1).

①Wind the copper pipes (ϕ 4,5,6;t=1) around a round-bar or pipe, etc, making it coil-shaped.

②Weld the entry and exit of copper pipes to the power connection with silver solder.

③After verifying the flow of the cooling water, adjust the work coil shape and equalize the temperature distribution.

The work coil installation condition (a) may be used for testing apparatus with a length between the upper and lower grips of about 50mm. Also, fixing the work coil with resin will prevent deformation caused by contact during test piece desorption and help keep the coil shape stable.

(b) and (c) may be used for testing apparatus with a gap between the upper and lower grips. (b) coil is used in routine conditions. If the temperature at the center of the parallel portion of the test piece is low and the test temperature is between 700 and 900 ℃, (c) coil may be used (refer to attached figure 2).

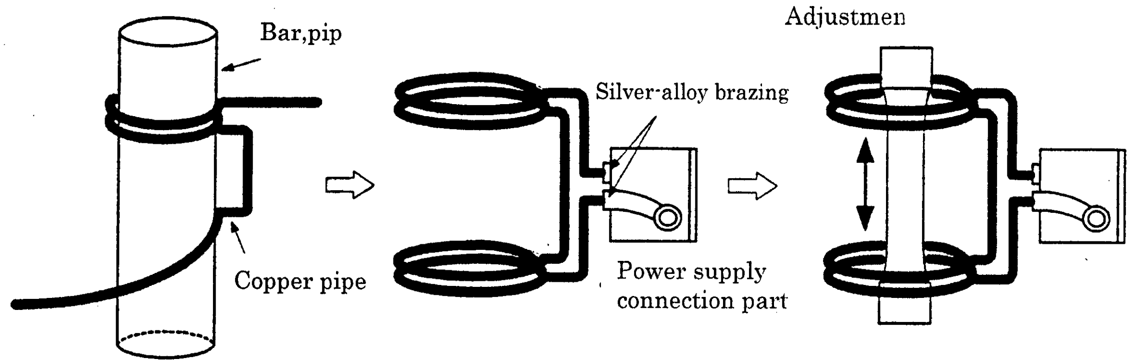


Figure1　Example of a work coil manufacture

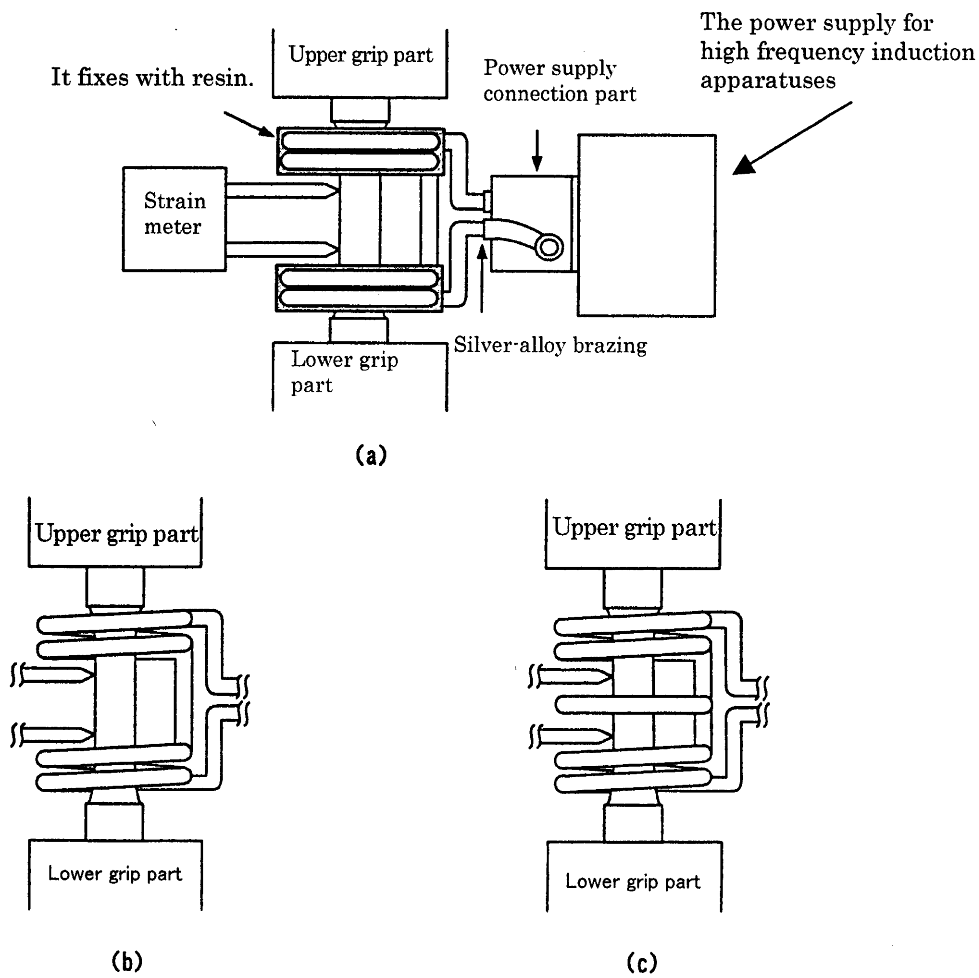
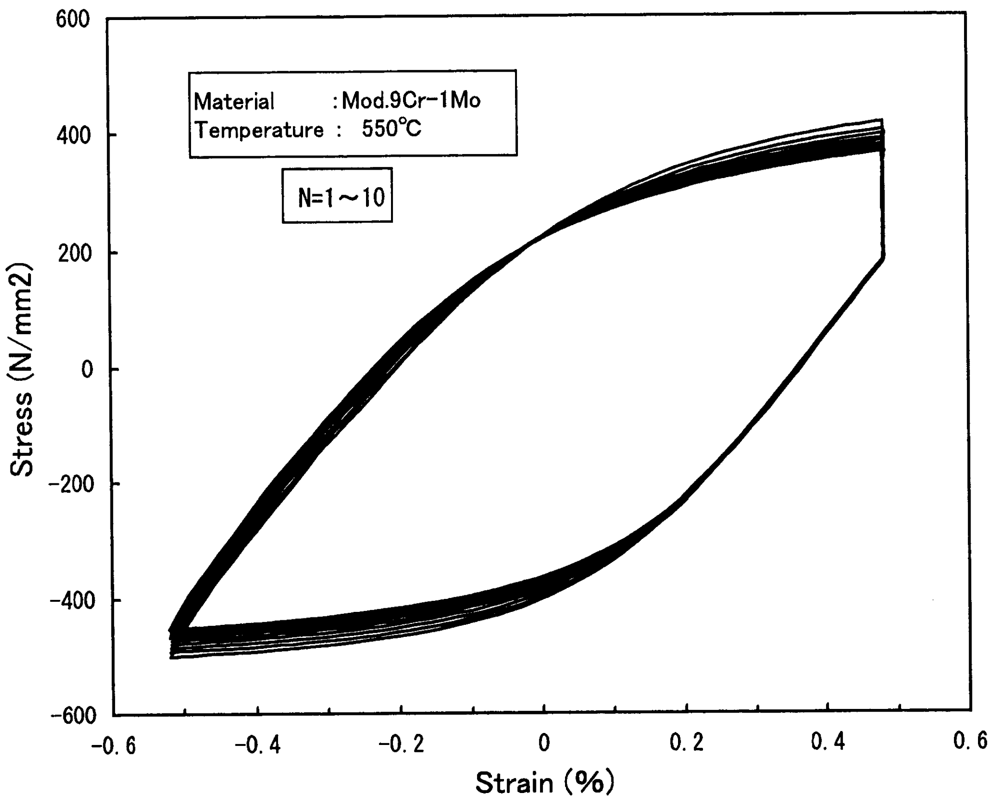


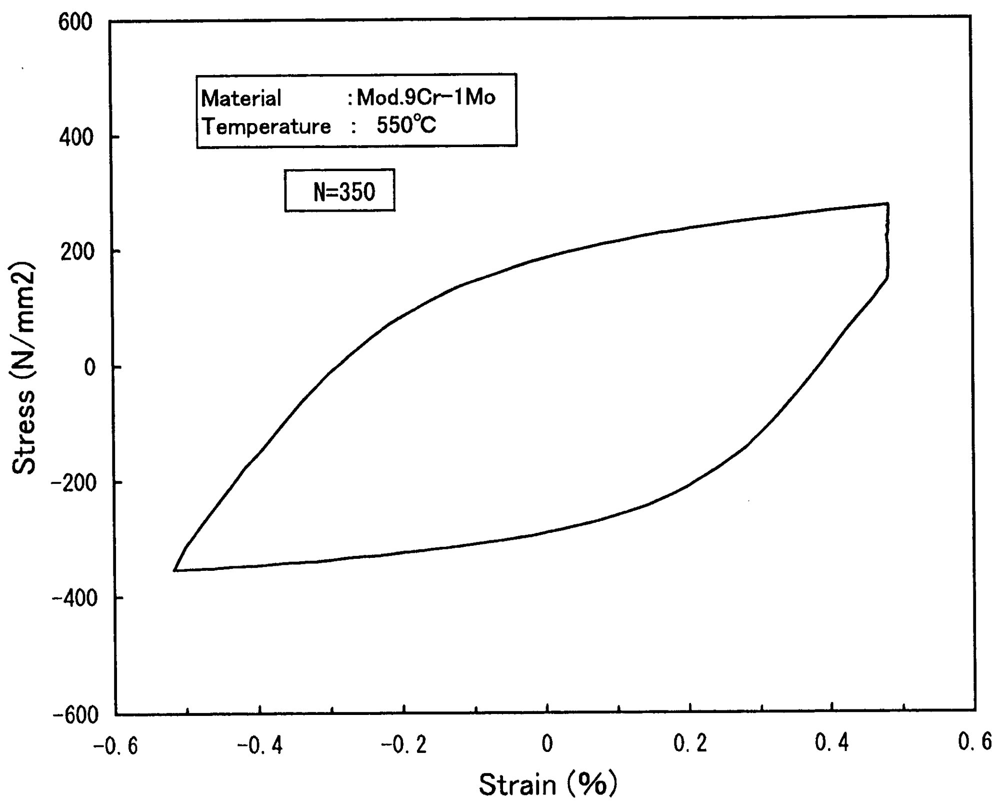
Figure2　Work coil attachment state

Appendix2.4-11 FBR metallic materials test data sheet (fatigue)

Test condition	Control method
1	A

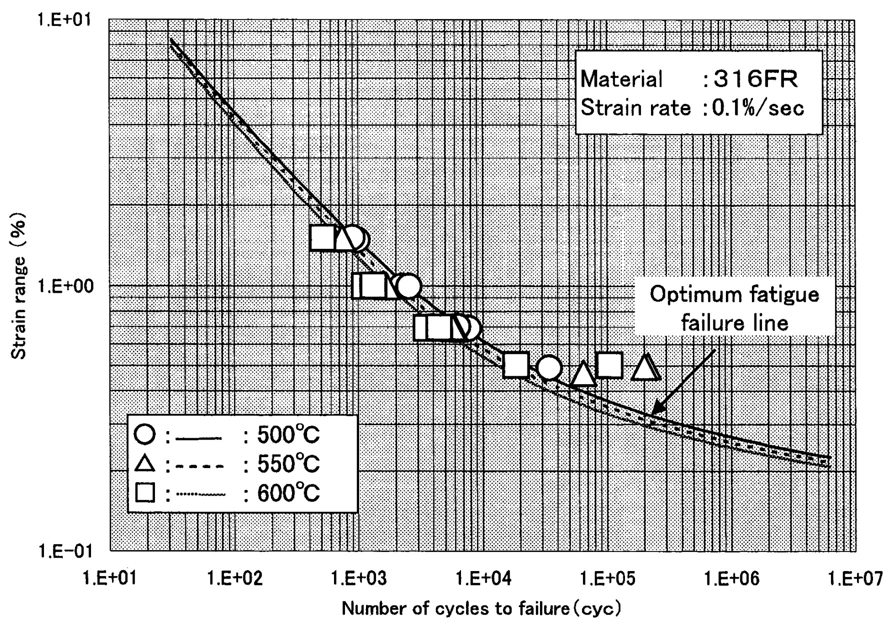
Test piece No	Strain kind	Strain waveform	Holding time(hr)		strain rate(%/sec)		Testing temperature (℃)	mean strain range (%)	Total strain range (%)	Innelastic strain range (%)	Nunber of cycles (cycles)	failure position	The maximum and the minimum stress in Nf/2 (N/mm^2)				
			Tensile side	Compression side	Tensile side	Compression side							cycles	σmax	σ' max	σmin	σ' min
HMH1B8	1	1	0	0	0.1	0.1	500	0	1.512	1.021	897	A	440	335.405		-351.546	
HMH8B9	1	1	0	0	0.1	0.1	500	0	0.992	0.597	2559	A	1200	273.557		-284.220	
HMH8B8	1	1	0	0	0.1	0.1	500	0	0.699	0.379	6316	A	3000	229.085		-236.699	
HMH1C2	1	1	0	0	0.1	0.1	550	0	1.507	1.017	747	A	380	321.999		-336.924	
HMH8C2	1	1	0	0	0.1	0.1	550	0	0.991	0.582	1702	A	900	284.827		-295.490	
HMH8C1	1	1	0	0	0.1	0.1	550	0	0.697	0.358	5750	A	3000	238.836		-247.362	
HMH8C0	1	1	0	0	0.1	0.1	550	0	0.495	0.206	199433	A	100000	208.975		-215.678	
HMH1C0	1	1	0	0	0.1	0.1	600	0	1.509	1.045	522	A	260	318.039		-335.091	
HMH8C5	1	1	0	0	0.1	0.1	600	0	0.995	0.606	1332	A	700	270.509		-282.093	
HMH8C4	1	1	0	0	0.1	0.1	600	0	0.692	0.366	4532	A	2200	230.908		-240.051	
HMH8C9	1	1	0	0	0.1	0.1	600	0	0.500	0.211	106796	A	55000	205.624		-213.856	



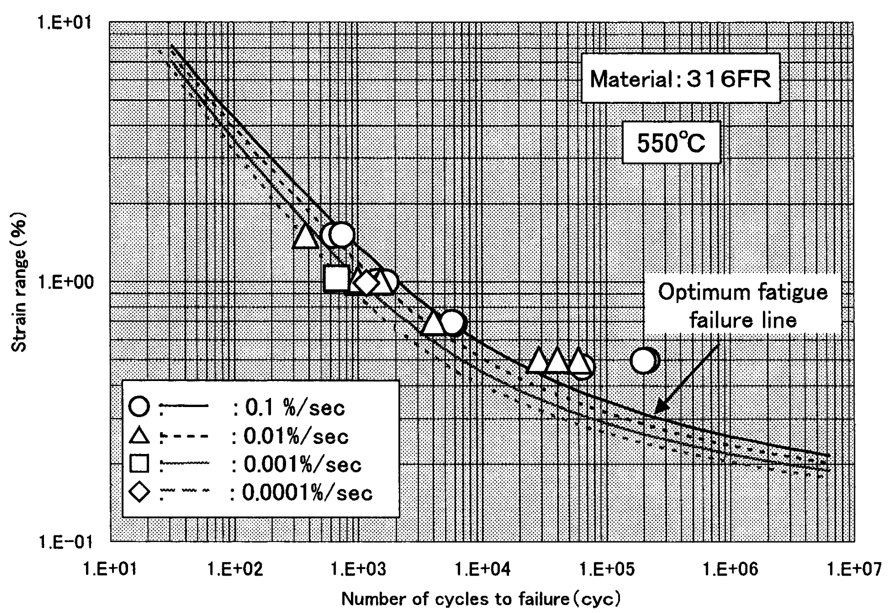


Appendix 2.4-12 Example of representation of hysterisis loop

Appendix 2.4-13 Low cycle fatigue-test data

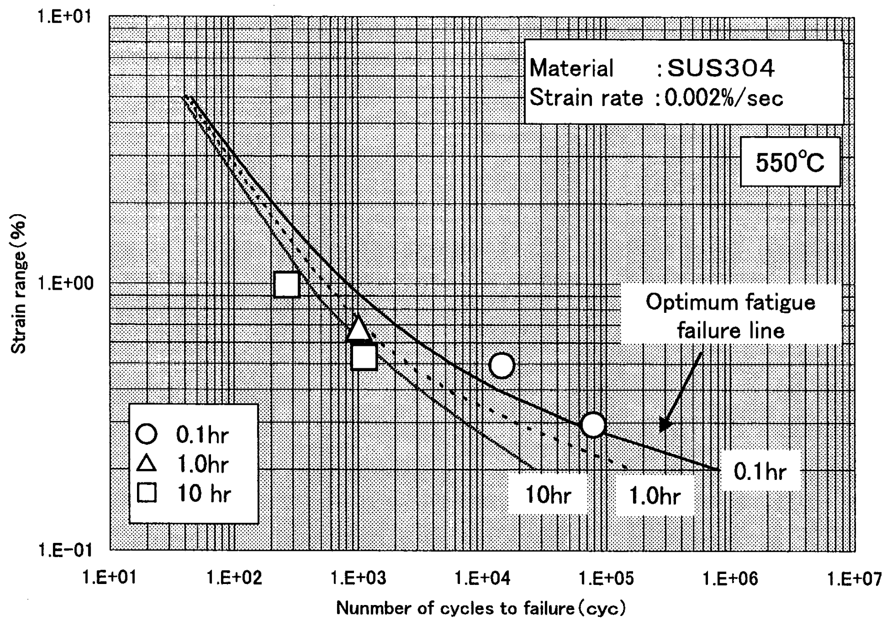


Low cycle fatigue life (temperature dependability)

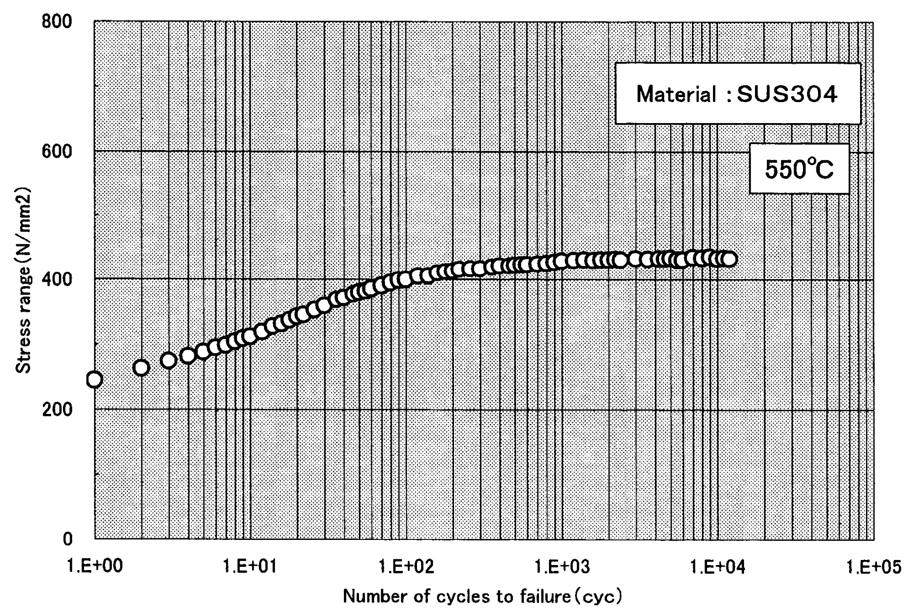


Low cycle fatigue life (the strain-rate effect)

Appendix 2.4-14 Prolonged creep-fatigue-test data



Creep fatigue life (550℃)



The example of representation of repeated-stress change

Appendix 2.4-15 Calibration of strain in fatigue test in sodium

To evaluate the fatigue strength of structural materials in sodium, strain of the parallel portion of the test piece needs to be calculated based on the displacement between collars as measured by an arm-type strainmeter (appendix 2.3-8). For the test in atmospheric air using the same shaped test piece, displacement between collars and strain of the parallel portion of the test piece are both measured by an arm-type strainmeter and press-type strainmeter. Naturally, strain is controlled by the arm-type strainmeter. Based on these results, calibration of strain in sodium should be performed by the following method, assuming that stress-strain behavior of the materials in atmospheric air is the same as in sodium.

(1) Total displacement between collars △LT can be expressed as the following formula (refer to attached figure 1), where △LG and △LR each denote total displacements of the parallel portion between collars and total displacement outside the parallel portion.

$$\Delta LT^{Na} = \Delta LG^{Na} + \Delta LR^{Na}$$

$$\Delta LT^{Air} = \Delta LG^{Air} + \Delta LR^{Air}$$

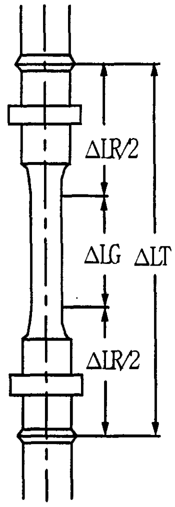
Here, Na and Air represent the values in sodium and in atmospheric air respectively.

(2) If the test piece material, temperature, and load conditions are the same, and, irrespective of test material history, the only test environment difference is the atmospheric air and the sodium, then its stress-strain behavior should be almost the same, which means that for specific displacement repetition between collars, △LT, △LG and △LR of sodium and atmospheric air can be assumed to be nearly equal.

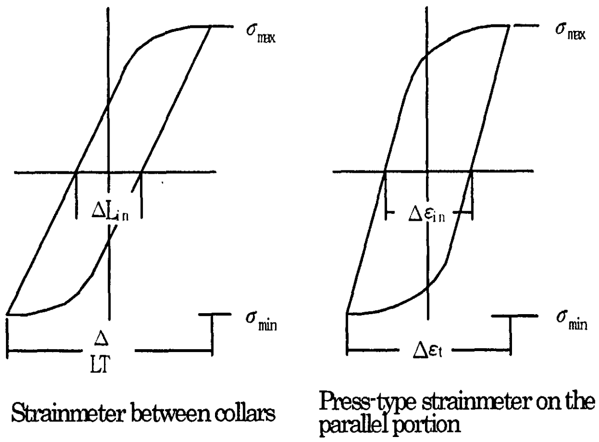
(3) Therefore, using the relationship of △LTair and △LGair as calculated from the test in atmospheric air, △LGna can be calculated by substituting △LTair with △LTna for testing in sodium when the number of failures Nf is 1/2.

(4) Regarding total strain, inelastic displacement △LGin of the parallel portion can be calculated by using the inelastic displacement between collars, △Lin, and substituting it in the relationship between △Lin and △LGin in atmospheric air, similar to (3).

For reference, figure 3 shows the strain calibration curve of testing in atmospheric air.



Referrence Figure 1 Test piece



Referrence Figure 2 Stress strain waveform diagram

Reference Figure. 3 Strain proofreading curve of Mod.9Cr-1Mo steel