New Products & Technologies

Fracture Toughness Testing System at Mizushima Works*

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1 Introduction

In securing the safety of offshore structures and pressure vessels, evaluation based on the fracture mechanics methods is widely used. In the toughness evaluation of steels to be used for these structures, tests are required which call for highly advanced techniques such as CTOD (crack-tipped opening displacement), K_{IC} (plane-strain fracture toughness), J_{IC} (plane-strain fracture toughness corresponding to ductile crack initiation), in addition to characteristics which can be obtained by simple methods represented by the conventional Charpy impact test. These methods for measuring fracture toughness based on fracture mechanics are stipulated by standards such as BS 5762[1], ASTM E399[2], and ASTM E813[3]. Since the above-mentioned tests are not so simple as the tensile test and Charpy impact test, they are carried out in the Research Laboratories. In recent years, however, fracture toughness test is so frequently demanded as a part of the manufacturing approval test or the commercial test that it became important to perform a great deal of tests correctly and in a short time.

In view of these present conditions, Mizushima Works has been endeavoring to build CTOD, K_{IC} and J_{IC} testing systems which are particularly frequently demanded out of the fracture toughness tests in order to achieve the development and improvement of high toughness steel and to meet the quality assurance demand of users. In the following, the fracture toughness testing system is outlined which was installed at Mizushima Works and is being operated successfully.

2 Configuration and Functions of Testing System

The fracture toughness testing system consists of a 5-tf electrohydraulic servocontrolled testing machine for fatigue pre-cracking, an electronic Instron type 25-tf testing machine for small-sized CT testing and elevated- and low-temperature tensile testing, a 50-tf electrohydraulic servocontrolled testing machine for fatigue pre-cracking and small-sized CT (compact test) and CTOD testing, a 300-tf electrohydraulic servocontrolled testing machine capable of a three-point bend CTOD test and pre-compression of steel plates up to 200 mm thick, and their respective controlling and computing units. Outlines of functions of the respective testing machines are summarized in **Table 1**. As examples of typical testing machines, the external views of the 50-tf and 300-tf testing machines are shown in **Photo 1**, and system configuration in **Fig. 1**.

Testing machines are arranged so that a series of testing processes ranging from fatigue pre-cracking to outputting of test data can be executed within the same building to facilitate speedy testing. Further, the test pro-

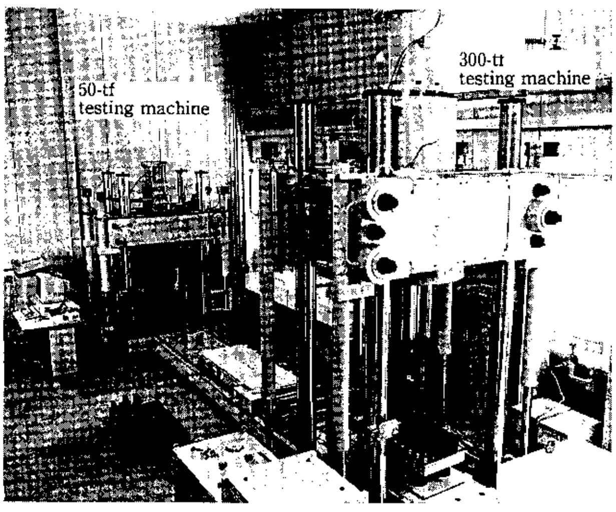

Photo 1 Overview of 50-tf and 300-tf fracture toughness testing machine

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Table 1 Summary of functions of fracture toughness testing system

No.	Item	5-tf Testing Machine	25-tf Testing Machine	50-tf Testing Machine	300-tf Testing Machine
1	Mechanism	Electro-hydraulic serve	Digital mechanical servo	Electro-hydraulic servo	Electro-hydraulic servo
2	Control method	Load control by servo closed-loop system	Load and stroke control by computor servo closed-loop system		
3	Application	Fatigue precracking of CT and CTOD specimens	1. CT test at temperatures between +500°C and −185°C 2. Tensile test at temperatures between +900°C and −185°C	1. Three point bend test and fatigue precracking at temperatures between RT and −196°C 2. CT test at temperatures between RT and −185°C	1. Precompression 2. Three point bend test of specimens not thicker than 200mm at temperatures between RT and −185°C
4	Capacity Max. load (tf) Max. stroke Max. crosshead speed	5 (dynamically) 7.5 (statically) ±25 mm 70 mm/s	25 (statically) 120 mm 500 mm/min.	50 (dynamically) 65 (statically) ±100 mm 180 mm/s	300 (statically) ±200 mm 200 mm/min
5	Dimensions (mm$D$ × mm$W$ × mm$H$)	1000×870×2030	880×1300×2700	1500×2000×3200	1500×2000×4360
6	Test program available	——	1. J_{Ic} test 2. K_{Ic} test 3. Load or strain controlled tensile test	1. CTOD test 2. K_{Ic} test 3. J_{Ic} test 4. K-value controlled fatigue precracking	1. CTOD test 2. K_{Ic} test 3. Precompression

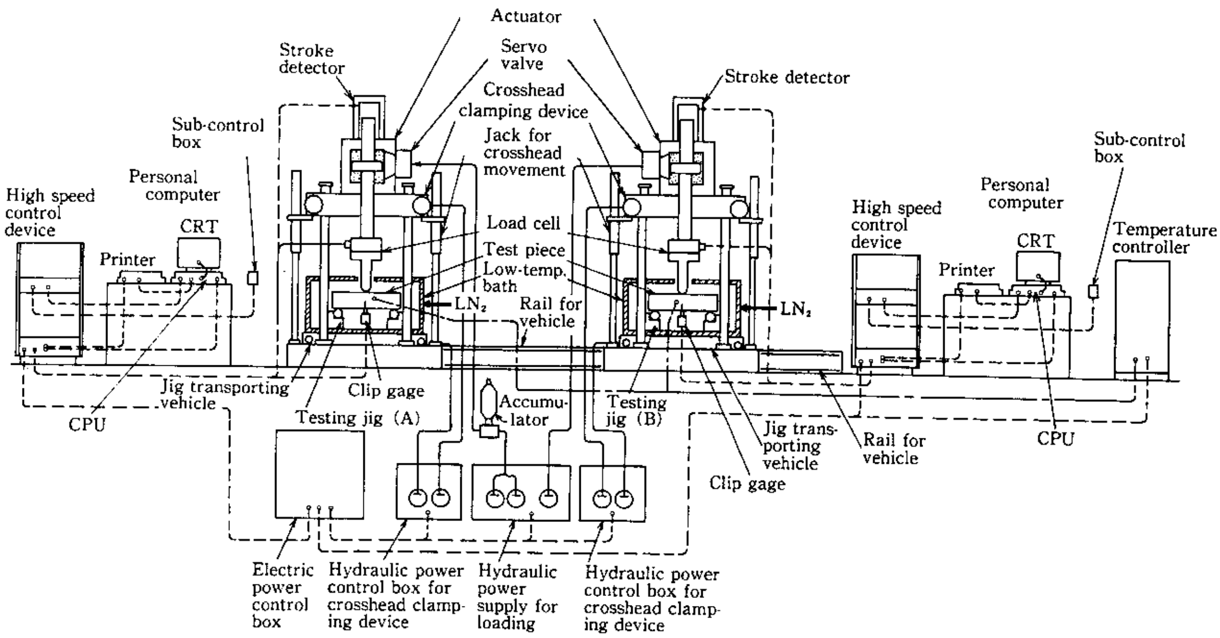

Fig. 1 System diagram of 50-tf and 300-tf fracture toughness testing machines

gram incorporates validity-evaluation formulae, which have been stipulated by the respective test standards, to permit logic judgment and output displaying, thereby enhancing the reliability of tests.

3 Features of Test System

3.1 Measurement of CTOD by Three-Point Bend Test

For safety evaluation of offshore structures such as jackets and pressure vessels such as LNG storage tanks, CTOD test is ordinarily employed. Fracture toughness of steels and welded joints to be used for them are judged mainly by CTOD. As offshore structures become large in size, steel plates used for them tend to be thicker. Since the LNG storage tank is used at a temperature of −163°C, tests which are matched with this temperature are required. The present testing system has been arranged so that a three-point bend test of heavy section steel plates with thickness of up to 200 mm can be performed. For this purpose, the system is provided with a 50-tf electrohydraulic servocontrolled testing machine for fatigue precracking and small-sized three-point bend tests, and a 300-tf electrohydraulic servocontrolled testing machine for large-sized three-point bend tests. The capacity for three-point bend tests of steel plates having a thickness of up to 200 mm was selected to cope with the increased thickness of steel plates used to construct offshore structures in deep-sea areas.

To introduce fatigue pre-cracking, it is necessary to keep the stress intensity factor not larger than a constant value (for instance, this value for BS 5762[1] is $0.63\sigma_Y\sqrt{B}$, where σ_Y and B are yield strength and specimen thickness, respectively). In the 50-tf testing machine, K-value (stress intensity factor) control is made possible in addition to a simple loading control, thereby permitting the introduction of fatigue pre-cracking of high accuracy.

In the CTOD test, the specimen must be kept at a prescribed temperature. Consequently, the entire specimen is accommodated in an exclusive-use cooling box, thereby permitting accurate control within a wide range from room temperature to −196°C using liquid nitrogen. The loading rate to the specimen must be within the range of a stress intensity factor of 15 to $80\,N\cdot mm^{-3/2}/s$ which is stipulated by BS 5762. The closed circuit system allows high-accuracy control, and further, displacement rate control is also made available. All tests are under computerized control, and loading in the test process, recording of data such as clip gauge displacement, calculation of CTOD throughout these analysis, and judgment of validity of the test are executed quickly and at high accuracy. A block diagram of the functions of the testing machine is shown in **Fig. 2** for the 50-tf testing machine taken as an example.

3.2 Measurements of K_{IC} and J_{IC} by Compact Test

When design and assessment of integrity are conducted on the basis of ASME Boiler and Pressure Vessel Code, Sec. III and Sec. XI, for nuclear pressure vessels, etc., static plane-strain fracture toughness (K_{IC} or J_{IC}) is used. Therefore, fracture toughness of steels to be used is assessed based on K_{IC} or J_{IC} as judgment standard. The fracture toughness of the steels must be obtained in accordance with ASTM E399[2] and E813[3], and ordinarily compact tests are used. The compact test is used to obtain plane-strain fracture toughness, and the specimen size required varies depending on the quality of material and the magnitude of fracture toughness. Namely, the higher the toughness of the material, the larger the specimen must be. However, specimens with a thickness of up to 50 mm are generally used.

Usually, the K_{IC} test is carried out at low temperatures, whereas the J_{IC} test is at elevated temperatures. Therefore, the system is designed so that the temperature of a compact specimen having a thickness of 50 mm at the maximum can be controlled within a very wide range from −196°C to +500°C at an accuracy of ±1°C. The control of loading to the specimen is of the closed

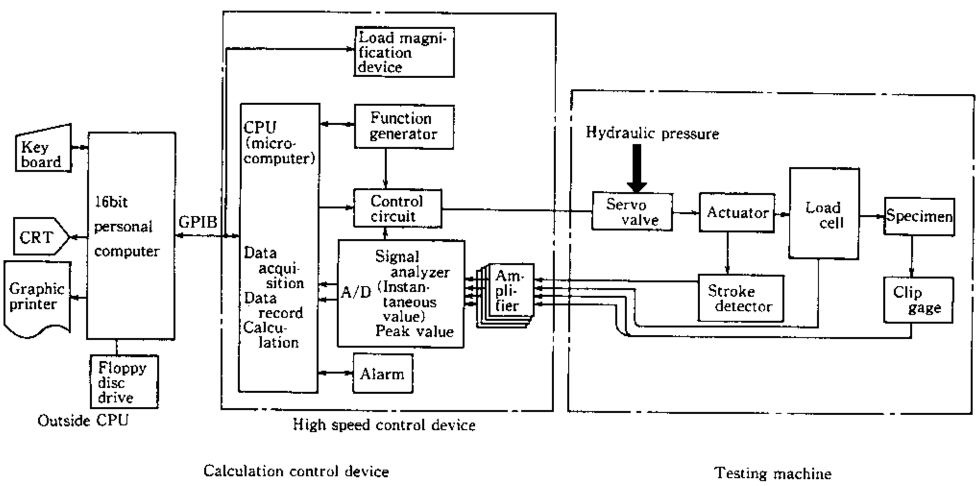

Fig. 2 Function block diagram of 50-tf testing machine

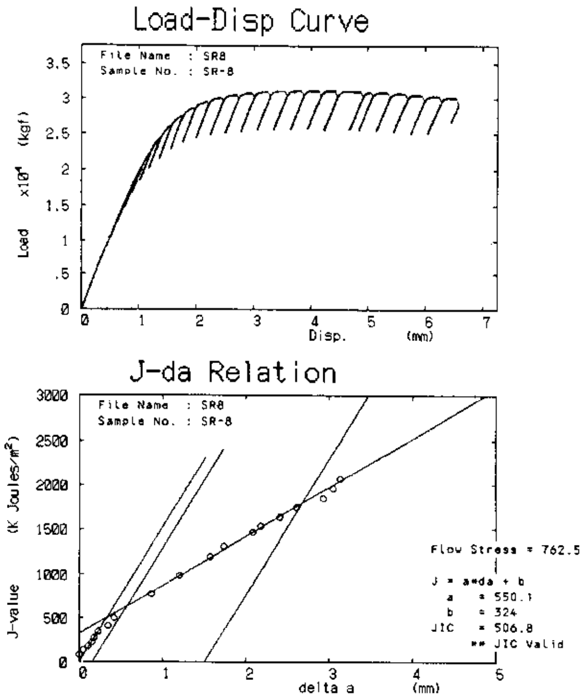

Fig. 3 Examples of a load-displacement curve and plot of J-value vs. crack extention for determining J_{IC} by unloading compliance method

loop type, and thus a test at a loading rate stipulated by the standard can be executed. In the J_{IC} test, sometimes a method called the "unloading compliance method" is used, which is to obtain the initiation and extension characteristics of ductile crack, using a single specimen. This method works in the following way: After the specimen is loaded up to an arbitrary load, about 10% of the load is reduced. From the relation between the load and displacement during unloading, the crack length is estimated. At the same time, from the area under the load-displacement curve immediately before unloading, J-integral is obtained. By repeating this process, the relation between the J-integral and the crack extension is obtained. This method requires high-accuracy measurements of load and displacement as well as computerized processing of the data. An example of actual execution is shown in **Fig. 3**.

For the plane-strain fracture toughness test, the 25-tf Instron type testing machine, the 50-tf electrohydraulic servocontrolled testing machine, and further, the 300-tf electrohydraulic servocontrolled testing machine can be used.

Yield strength, tensile strength and elastic constants at elevated or low temperatures, which are characteristics necessary for fracture toughness evaluation, can be measured with high accuracy in accordance with ASTM E8[4], ASTM E21[5], ASTM E111[6] and E231[7], using the 25-tf Instron type testing machine.

4 Summary

The fracture toughness testing system installed at Mizushima Works has been introduced in the above. In this system, the three-point bend test and compact tension test use programs conforming to their respective standards to conduct computerized control, data recording, computation of measured values, and validity judgment, thereby achieving the speeding-up and reliability improvement of the tests.

Further, the new testing system has been provided, taking into consideration the increase in size of offshore structures accompanying construction at deep-sea areas, with the three-point bend test capability up to 200-mm thick heavy section steel plates.

With demand for the quality of steel plates getting higher and diverse in recent years, the system at Mizushima Works has proved to be a powerful means for quality assurance of high strength steel plates, including the essential testing phases toward improvements and developments.

References

1) BS 5762: "Method for Crack Opening Displacement (COD) Testing"
2) ASTM E399: "Standard Test Method for Plane Strain Fracture Toughness of Metalic Materials"
3) ASTM E813: "Standard Test Method for J_{IC}, a Measure of Fracture Toughness"
4) ASTM E8: "Standard Test Method for Tension Testing of Metalic Materials"
5) ASTM E21: "Standard Recommended Practice for Elevated Temperature Tension Tests of Metalic Matelials"
6) ASTM E111: "Standard Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus"
7) ASTM E231: "Standard Method for Static Determination of Young's Modulus of Metals at Low and Elevated Temperatures"