[**Analysis**]

Development of Material Strength Evaluation Technology that Supports Social Infrastructures

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Abstract

Pure copper is used as conductors of electrical equipment such as generators. Pure copper and other metals can lead to fatigue fracture when a load is repeatedly applied for a long time. When designing a product, it is necessary to determine fatigue life for pure copper, but since the testing speed is slow for a conventional fatigue test, the verification period would take a very long time.

To resolve this challenge, we developed a technology for material strength evaluation using a testing system by which a stable load can be applied even with a high cycle loading of more than 50 times the conventional metal fatigue testing speed. As a result of this evaluation technology development, any testing can be conducted quickly, and meet the requirements for reproduction of long-time working conditions for a product. In addition, the adequate product lifetime can be predicted at a product design stage.

1 Preface

To realize light mass and compact design of the product, the industry strongly calls for an improvement of such reliability evaluation technology. For example, the product lifetime of a large-sized generator may span for over several decades. As a result, a mechanical load exerted on conductors repeatedly numbers more than hundreds of millions of times.

In many cases, pure copper is used as conductors. Compared with steel materials used as structural members, however, pure copper has low strength and is unsuitable for use as a structural (strength) material. For this reason, generally, a study[(1)(2)] regarding a super-long life, where the number of stress repetitions exceeds tens of millions of times, is extremely rare. Since pure copper is soft, it can lead to permanent deformation. In the fatigue test, therefore, the testing load must be controlled with high accuracy and at a high speed.

To manage such an issue, we conducted application research into a high cycle fatigue testing machine (testing speed 1 kHz) made by MTS Systems Corporation, a test systems supplier in the US ("MTS" hereafter). With this machine, one billion times of repeated stress test was completed in 11 days while a conventional testing machine (testing speed 33 Hz) may last about one year. In addition, we systematically conducted experiments with varying average stress and clarified the effect on fatigue life. This paper introduces fatigue testing technology applicable to any of these conditions.

2 Development of Evaluation Technology

In regard to strength characteristics obtained from tensile tests on materials, there are cases that strength characteristics are lowered to half or below due to effects of repeated stress load, ambient temperature, mean stress, surface effect, size effect, and variable stress. Degrees of respective effects can differ according to materials adopted. For example, if comparison is made on tests done at a room temperature and a high temperature, the plastic strain is remarkable at a high temperature and a change in material is intensified during testing. For this reason, it is necessary to design a control that can follow up the change in material in order to carry out the evaluation with an adequate load. Based on such a technical background, the features of the testing machine that meets the requirement of pure copper are described below.

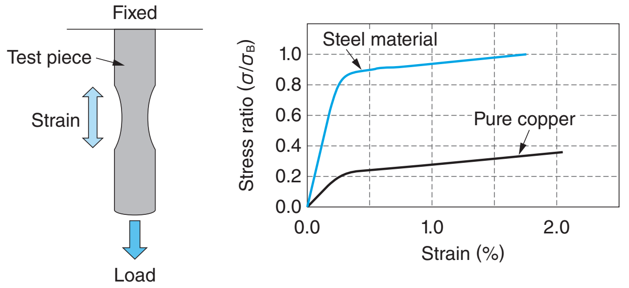

Fig. 1 Stress-Strain Curves of Steel and Pure Copper

When strength characteristics are compared between steel and pure copper, pure copper has a feature of causing deformation with a low stress.

2.1 Features of Pure Copper and Necessary Conditions for the Testing Machine

Fig. 1 shows stress-strain curves of steel and pure copper. The stress ratio (σ/σ_B) defines the rate of stress when the tensile strength of each material is assumed to be unity. For steel, plastic strain appears at a value around 0.8. Conversely, pure copper gives rise to plastic strain around 0.2. Pure copper yield stress is very low compared with steel. Since there may be an occasion when this yield stress is exceeded while a product is used, a large deformation can occur. In the case of testing performed in a region where such a large deformation appears, a testing machine previously aforementioned may be needed so that a proper load can be exerted. For this reason, we adopted a servohydraulic fatigue testing machine. This is a load control type model.

2.2 High Cycle Fatigue Testing Machine

If a conventional test system is used in a super-long life region, verification test requires a very long time. Since a high-speed testing technology utilizes ultrasonic waves, the testing speed is high and the required conditions can be satisfied. It is, however, impossible to perform testing under loaded control. For these reasons, an accurate load cannot be applied in the case of testing on pure copper. Consequently, it became necessary to adopt a high cycle fatigue testing machine that is capable of loaded control. Consequently, a servohydraulic fatigue testing machine with a testing speed specified at 1 kHz was introduced. This testing machine assures high test accuracy at the maximum testing speed of 1 kHz by using a voice coil servo valve.

In order to verify the capability of adequate fatigue test with a testing machine with such a mechanism, we confirmed the stability of load waveforms, temperature changes in fatigue testing processes, and the difference in its lifetime based on the testing speed. **Table 1** shows specifications of 1 kHz servohydraulic fatigue testing system and **Fig. 2** shows an external appearance of the fatigue testing system.

Table 1 Specifications of 1 kHz Servohydraulic Fatigue Testing System

Specifications of a servohydraulic fatigue testing system made by MTS Systems Corporation in the US are shown. This system makes it possible to perform testing at the maximum speed of 1 kHz.

Item	Specifications
Capacity	±25 kN
Speed	1 kHz Max.
Environment	Atmosphere
System	Voice coil servo valve
Control	Amplitude adjusting function (PID control)
Others	Servo valve for low speed Vibration control, soundproof

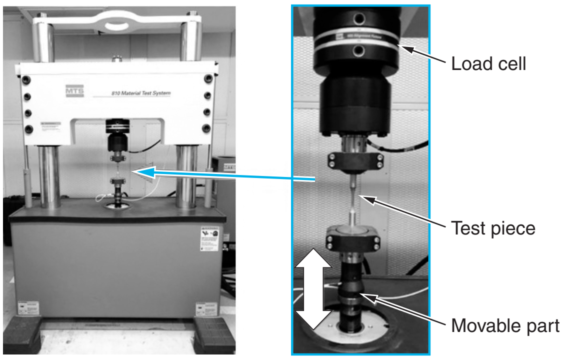

Fig. 2 1 kHz Servohydraulic Fatigue Testing System

An external appearance of the fatigue testing system is shown.

2.2.1 Test Piece and Testing Conditions

The test piece was tough pitch copper (C1100) conforming to JIS H3140. The mechanical characteristics are 293 MPa for 0.2% proof stress and 302 MPa for tensile strength. **Fig. 3** shows the specimen for fatigue test. For the surface finish for the test piece, Emery paper was used for up to #600 and polishing was applied in the axial direction.

Regarding the test conditions, a complete one-side swing was at stress ratio R = 0, loading waveform is sinusoidal, and testing speed is 1 kHz. The test was carried out at room temperature under the atmospheric environment. Forced cooling was not conducted during the test. The number of fractures

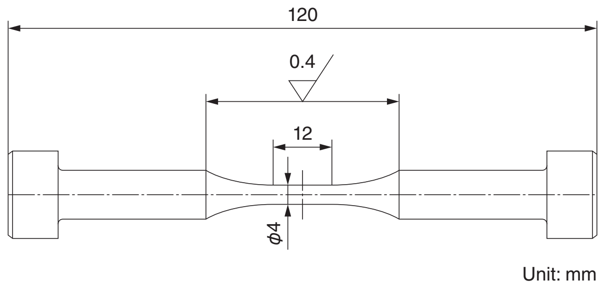

Fig. 3 Specimen for Fatigue Test

A button head type round-bar test piece is shown. This test piece is used for the 1 kHz servohydraulic fatigue testing system.

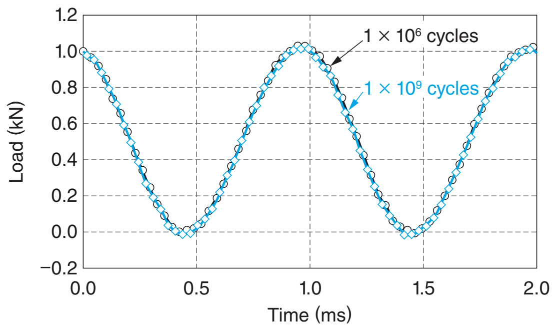

Fig. 4 Load Waveforms

We confirmed the stability of load waveforms in the test process under the conditions of a testing speed f = 1 kHz, stress amplitude $\sigma_a = 40$ MPa, and stress ratio R = 0. In all tests, the load was applied in a stable manner.

is defined as the cycles of occasions when a fatigue crack develops in the test piece, thus exceeding 1 mm of displacement, and the auto-stop device worked in the testing system.

2.2.2 Load Waveform Stability

In order to confirm whether the load is accurately exerted on pure copper shown in **Fig. 1** for the fatigue test set at a testing speed of 1 kHz, a load waveform output generated by a load cell was used. **Fig. 4** shows load waveforms. Since waveforms of repetition number 1×10^9 cycles coincided with those of 1×10^9, it is obvious that the load was accurately working during the process of total fatigue test.

2.2.3 Temperature Change during Testing

Fig. 5 shows temperature rise in the test piece. During the process of fatigue test at a testing speed of 1 kHz, we confirmed the heat generated by friction caused in the test piece. To define the position of measurement, a black spot was assigned in the center of the test piece and measurement was carried out by means of a radiation thermometer.

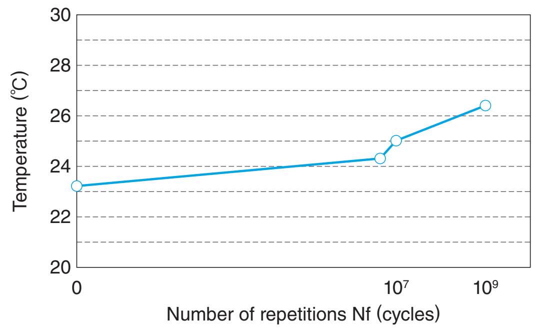

Fig. 5 Temperature Rise in Test Piece

We confirmed the temperature rise in the test process under the conditions of a testing speed f = 1 kHz, stress amplitude $\sigma_a = 40$ MPa, and stress ratio R = 0. In all tests, temperature changes were kept around 3K.

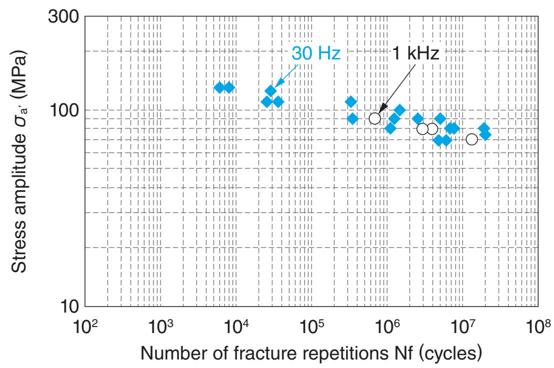

Fig. 6 S-N Curve (Testing speed dependence)

We confirmed the effect of difference in testing speed upon fatigue life at 1 kHz under the condition of a testing speed f = 30 Hz. There was almost no effect of speed upon life within the scope of this study.

Regarding temperature changes from the fatigue cycles 4×10^6 to 1×10^9, there was a rise of approximately 3K. This shows that there is no high temperature rise that can change the mechanical properties of the material.

2.2.4 Testing Speed Dependence

Fig. 6 shows the S-N curve (testing speed dependence), where the S-N curve shows the relationship between stresses repeatedly applied at a constant amplitude and the number of repetitions accumulated until fracture. This is a result of testing conducted at the testing speed of 30 Hz and 1 kHz.

It was conducted to investigate the effect of testing speed that affects the fatigue life. The plots for test speeds of 30 Hz and 1 kHz almost overlap. This suggests that influence of testing speed upon its life is minimal.

According to the obtained results, we could verify that there is no problem in 1 kHz fatigue test.

3 Result of Testing

We will introduce the experimental results when the mean stress changes as an influencing factor on fatigue life. The test piece adopted is tough pitch copper (C1100) conforming to JIS H3140. Simulating the state of soldering, furnace-cooling heat treatment was carried out under the condition that 720～780℃ was maintained for tens of seconds. For mechanical characteristics, 0.2% proof stress was 63 MPa and tensile strength was 204 MPa. For the testing on life region below 1×10^7 cycles, we used a servohydraulic fatigue testing system which is a general-purpose testing machine made by MTS. The testing speed was 30 Hz. The test piece used for testing at room temperature was a round bar whose portion to be tested had a parallel section of 8 mm in diameter.

3.1 Mean Stress

Fig. 7 shows S-N curves with stress ratios R = −1 and R = 0. Since it is difficult to read out the effect of mean stress from the S-N curve at a glance, explanations below will use an endurance fatigue limit diagram where mean stress is applied on the axis of abscissas and stress amplitude is applied on the axis of ordinates. For pure copper, a clear fatigue limit does not appear on the S-N curve. As a result, we established an endurance fatigue limit diagram based on the lifetime where the number of repetitions attaining to fracture is 1×10^6, 1×10^7, and 1×10^8 cycles, respectively.

Fig. 8 shows an endurance limit diagram under the condition of a room temperature. Mark △ shows an empirical point at stress ratio R = −1 and Mark ○ shows the one at stress ratio R = 0. In any endurance limit diagram, a tendency can be seen such that the stress amplitude lowers when the mean stress increases. Based on the result of experiments, we made comparison of repetition numbers through the application of modified Goodman diagram[(3)], a general approach used for steel materials. The modified Goodman diagram is an endurance limit diagram that is obtained from lines combining the plotted points on a graph where stress amplitude of endurance limit at stress ratio R = −1 is expressed on the axis of abscissas and tensile strength on the axis of ordinates. For the life of 1×10^7 cycles, a good relationship with the modified Goodman diagram could be confirmed. For a short life of 1×10^6 cycles, however, the Modified

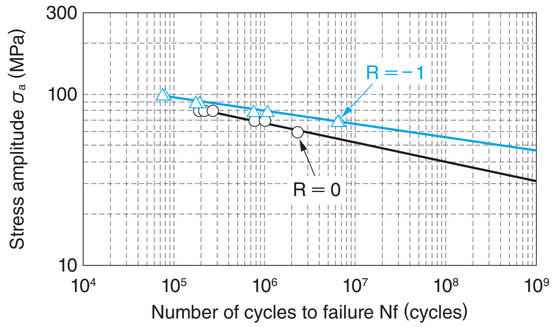

Fig. 7 S-N Curves with Stress Ratios R = −1 and R = 0

The relationship between stress amplitude and life at room temperature for a stress ratio of R = −1,0 is shown.

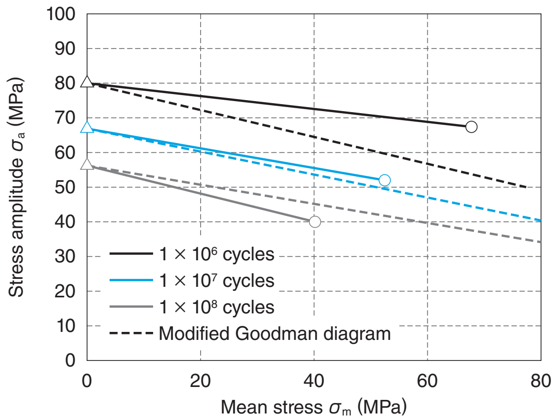

Fig. 8 Endurance Limit Diagram

The effect of mean stress upon fatigue life has been clarified.

Goodman diagram could not be applied because the effect of mean stress upon the lowering of stress amplitude became feeble. In the case of a long life of 1×10^8 cycles, the effect of mean stress upon the lowering of stress amplitude became larger than that of fatigue cycles 1×10^6 and 1×10^7 cycles. Accordingly, the point crossing the axis of abscissas was far lower than the tensile strength and therefore, the modified Goodman diagram could not be applied.

3.2 Super-Long Life Region

Fig. 9 shows the S-N curve in the super-long life region obtained from the fatigue test at a testing speed of 1 kHz. The dotted line indicates 50% fracture probability. Although the repetitive number 1×10^9 of stress amplitude $\sigma_a = 40$ MPa resulted in no fracture, it was defined as “fracture” to determine the S-N curve. This S-N curve almost coincided with the result of conventional study[(3)] for up to 4×10^8 cycles. Together with the result for this time,

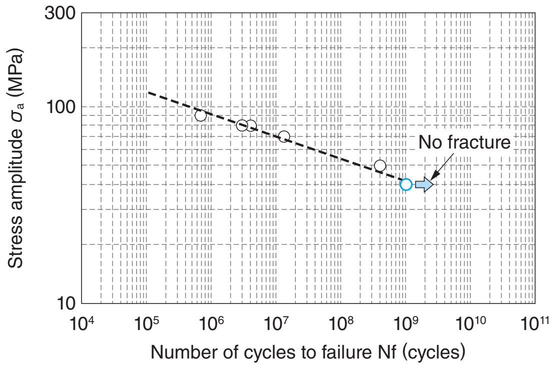

Fig. 9 **S-N Curve (Super-Long Life Region, R = 0, Room Temperature)**

The S-N curve in the super-long life region is shown, obtained from testing at a testing speed of 1kHz.

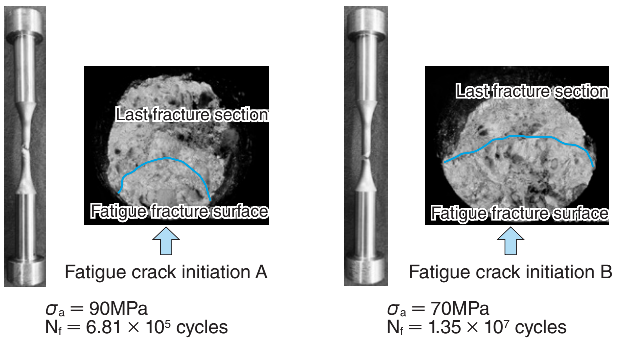

Fig. 10 **Fractured Test Piece and Fracture Section**

A domain of fracture section at each stress level is shown, obtained after the fatigue test. When the stress level is lowered, the fracture section is widened.

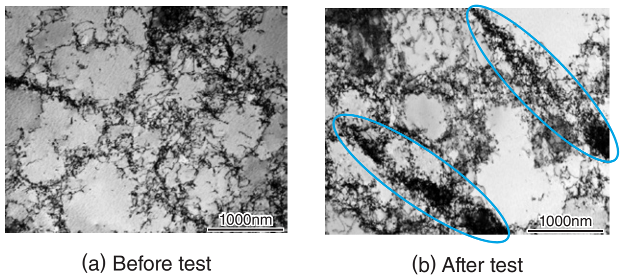

Fig. 11 **Observation Result of Dislocation by TEM**

Changes in dislocation before and after the test are shown. Under the magnification of 30,000, it is possible to identify the accumulation of dislocation on the slip plane indicated by circles.

it is now possible to achieve life estimation extended to the super-long life region.

4 Future Prospects

4.1 Observation of Metallic Structure

Fig. 10 shows an example of a macroscopic photo showing a fractured test piece and its fracture section observed by the aid of optical microscope when the S-N curve was established. The fractured position is not around the shoulder part or a round part, but in the vicinity of the center part of the test piece. Judging from the photo of the fracture section, the start point of fracture is presumed to be around A and B indicated by the arrows. It can be anticipated that fracture can be wide if stress is small. This resembles the result of past experiments(3) and that of experiments on steel materials.

Fig. 11 shows the observation result of dislocation by a Transmission Electron Microscope (TEM). As a specimen, a test piece was used where no fracture was seen after 1×10^9 cycles. Meanwhile, we used a method of electrolytic polishing to produce the specimen under the condition of no stress.

Observation was carried out to confirm a phenomenon called "plastic strain." This phenomenon appears as a symptom of metal destruction. Plastic strain is caused when neighboring atoms move into a void of atoms existing in a crystal (lattice defects). Comparing the test piece before and after testing, the slip plane of the crystal indicated by a round bar shows a part considered to be stacks of dislocation. This implies that plastic strain goes on even at a stress level of 1×10^9 cycles and finally leads to fracture. Since pure copper is considered free from an endurance limit, by identifying the index of fatigue limit from a microscopic point of view, it is possible to design with higher accuracy with due consideration to the fatigue mechanism.

4.2 Variable Load

Any load exerted on working machines and structures is changing. For a method of fatigue life presumption applied to such a changing load, a linear accumulated damage law (Miner's Law) is used.

The Miner's Law is a hypothesis that failure occurs when the cumulative total of the number of repetition number ratio to each corresponding stress to life reaches 1. If all changing stresses are greater than the endurance limit, the Miner's Law is applicable. This point is clarified by past research(4)(5). According to research(1) by Watanabe, et al., relating to the effect of low stress load in super-long life region exerted upon tough pitch copper under the condition of changing load, the Miner's Law showed approximately 0.5 as a result of two-tier double testing (a level of stress and repetition number being 2, respectively). Accordingly, it is reported that the Miner's Law can be satisfied if the S-N curve is amended. When a fatigue testing machine for plane bending is used, in which a machine was used at the time of the aforementioned research, there is limitation in loading type and control, thus failing in terms of superb waveform control.

Given, we are currently conducting fatigue test on actual loads by using a servohydraulic fatigue testing system in order to promote evaluation based on the Miner's law. Since the obtained result is used to improve fatigue life prediction accuracy under exertion of a changing stress, the gradient of S-N curve is amended so that the Miner's law comes closer to 1. In addition, a mechanism to shorten the fatigue life will be analyzed to realize lifetime prediction.

5 Postscript

We established a fatigue strength design standard for pure copper. This standard can be applied to various our models. The demand for reliable materials continues to increase year by year in order to achieve high output, high energy density and long life of electrical equipment.

Going forward, in order to contribute to the competitiveness of our products, we will promote R&D activities for fatigue strength design by exploring the mechanism of fatigue at the molecular and atomic level.

《References》

(1) Hiromitsu Watanabe, Haruo Yamamoto, Keiji Misawa, Mitsuaki Otsuka: "Transactions of the JSME (in Japanese) (Revision A)," Vol.66, No.651, 2000, pp.2044-2048
Published by The Japan Society of Mechanical Engineers

(2) Takeo Kuritani, Kazumune Katagiri, Akira Omura, Tetsuro Shiraishi: "Transactions of the JSME (in Japanese) (Part 1)," Vol.40, No.337, 1974, pp.2453-2461
Published by The Japan Society of Mechanical Engineers

(3) N. E. Frost, K. J. Marsh, L. P. Pook: "Metal Fatigue," Oxford Univ. Press 1974

(4) Hiroshi Nakamura: "Transactions of the JSME (in Japanese)," Vol.73, No.621, 1970, pp.1350-1358
Published by The Japan Society of Mechanical Engineers

(5) Hiroshi Nakamura, Takeshi Horikawa, Yoshio Kamata, Narikazu Yamaji: "Transactions of the JSME (in Japanese) (Part 1)," Vol.39, No.318, 1973, pp.472-479
Published by The Japan Society of Mechanical Engineers