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Application News

Ultrasonic Fatigue Testing System USF-2000A
Electron Probe Microanalyzer EPMA-8050G

High-Temperature Gigacycle Fatigue Test of Inconel 718 and Element Distribution Measurement on a Fracture Surface

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User Benefits

- Fatigue testing at 20 kHz can be performed using an ultrasonic fatigue testing machine, and 10^9 cycle fatigue tests can be completed in about 14 hours.
- High-temperature fatigue tests can be performed by using a combination of an ultrasonic fatigue testing system and an induction heating furnace.
- The origins of fatigue fractures and inclusions can be identified by observations and element distribution measurements using an electron probe microanalyzer.

■ Introduction

Inconel 718 has excellent heat and corrosion resistance and high strength. Its mechanical properties can be maintained even under high-temperature environments, which is why it is used in harsh environments, such as in the jet engines and turbine blades in the aerospace industry, and in gas turbines and nuclear power plant parts in the energy industry. In these applications, long-term reliability is crucial, making fatigue testing essential. However, this can be time-consuming; for example, gigacycle fatigue testing exceeding 10^9 cycles takes three to four months at a frequency of 100 Hz when using a conventional fatigue testing machine. But with the USF-2000A ultrasonic fatigue testing system, tests performed at a frequency of 20 kHz can be completed in approximately 14 hours.

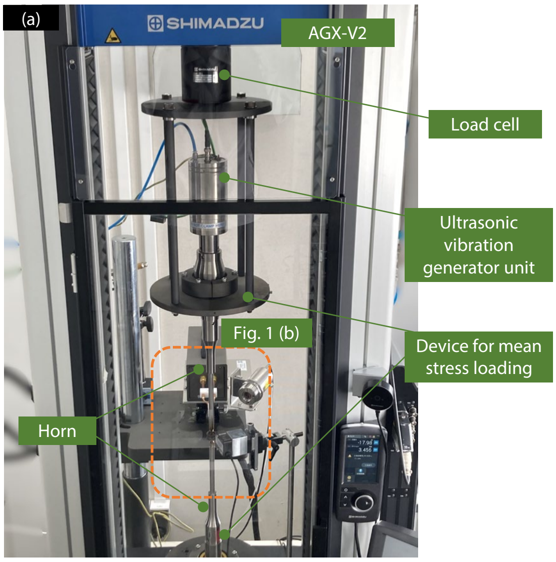
This article describes using the USF-2000A to perform gigacycle fatigue tests on Inconel 718 at 600 °C. In addition, the EPMA-8050G, which is an electron probe microanalyzer (EPMA™), was used to observe the fatigue fracture surfaces and measure the element distribution.

■ Measurement System

Fig. 1 shows a view of the tests. A mean stress was applied to the test specimen by a device for mean stress loading, and an ultrasonic vibration generator was attached to the device for mean stress loading. To prevent heating of the ultrasonic oscillator, rods were attached above and below the test specimen. The temperature of the heating furnace was controlled using a radiation thermometer. For this purpose, heat-resistant black paint was applied to the temperature measurement area of the test specimens in advance. Table 1 shows the configuration of the equipment used in these measurements.

Table 1 Equipment Configuration

Ultrasonic Fatigue Testing System	:	USF -2000A
Precision Universal Testing Machine	:	AGX™-V2
Testing Jig	:	Device for mean stress loading
Software	:	Super Sonic
Induction Heater	:	EASY HEAT
Radiation Thermometer	:	FT-H10 (KEYENCE)
Laser Doppler Vibrometer	:	VibroGo
Electron Probe Microanalyzer	:	EPMA-8050G



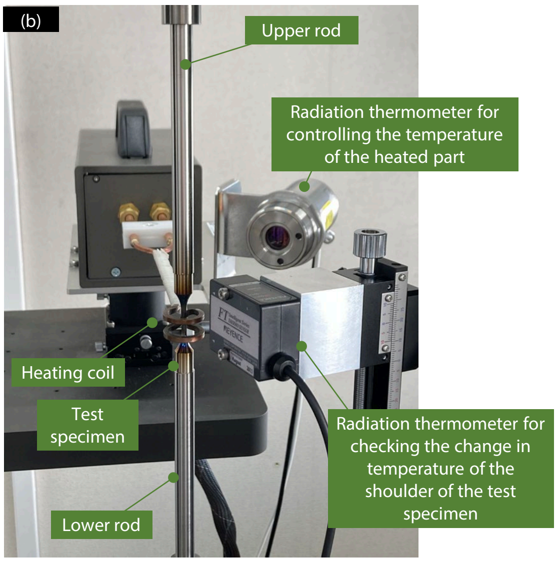


Fig. 1 Test Setup
(a) External View of the Apparatus (b) Around the Test Specimen

■ Temperature Distribution Measurement

To calculate the stress in a test specimen, the distribution of elastic modulus from the temperature distribution must be taken into consideration. Therefore, the temperature distribution of the test specimen under the measurement temperature conditions was measured in advance. In these tests, the test specimens were heated so that the temperature at the center was 600 °C. The temperature distribution of the test specimen was measured using thermocouples. The test specimen temperature distribution measurement results are shown in Fig. 2.

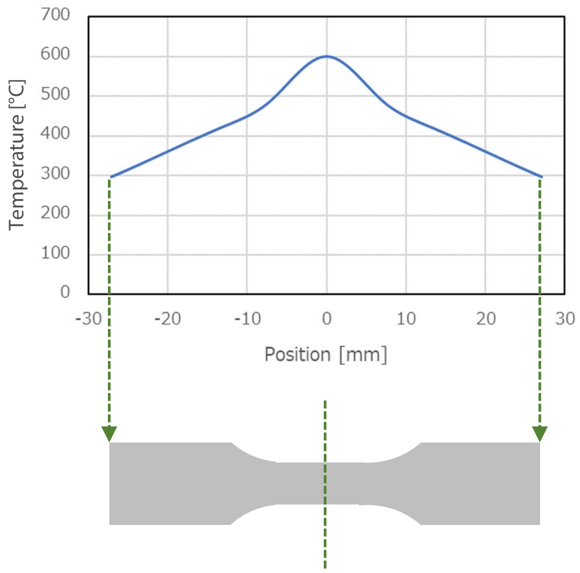


Fig. 2 Test Specimen Temperature Distribution

■ Adjusting Length of Test Specimens

The lengths of the test specimens were adjusted to match the resonance frequency of the horn. In these tests, the shoulder lengths of the test specimens were adjusted so that their resonance frequency was equal to that of the horn at 20.02 kHz. First, three types of test specimens were prepared with different shoulder lengths. Then they were attached to the upper and lower rods and heated so that the temperature distribution was the same as during measurement. Next, the resonance frequency of each test specimen was measured. Fig. 3 shows the relationship between the shoulder length of the test specimen and the resonance frequency. It was found that the shoulder length needed to be 10.9 mm to achieve 20.02 kHz.

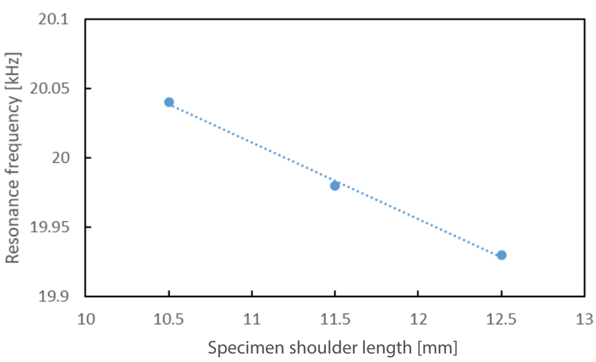


Fig. 3 Relationship between Test Specimen Shoulder Length and Resonance Frequency

■ Distribution of Elastic Modulus Due to Temperature and Calculation of Stress

As shown in Fig. 2, the temperature in the test specimen varies depending on the distance from the induction heating furnace during measurement, so the elastic modulus in the test specimen varies. Calculating the stress must take into consideration the distribution of elastic modulus, so it is necessary to separately calculate the elastic modulus at room temperature and at 600 °C. The elastic modulus at room temperature was determined by attaching a strain gauge to a test specimen and then performing a tensile test with the AGX-V2. Fig. 4 shows a view of the tensile test. The elastic modulus at 600 °C was calculated from the density of the material obtained from a density meter and the length of the shoulder of the test specimen, which was 10.9 mm. Fig. 5 shows the relationship between elastic modulus and temperature. For details of the stress calculation, refer to Reference (1).

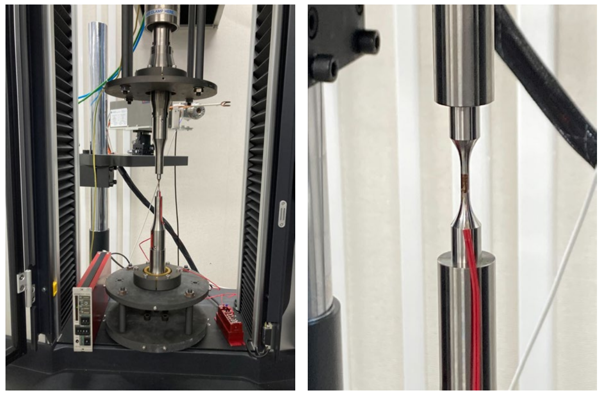


Fig. 4 View of the Tensile Test

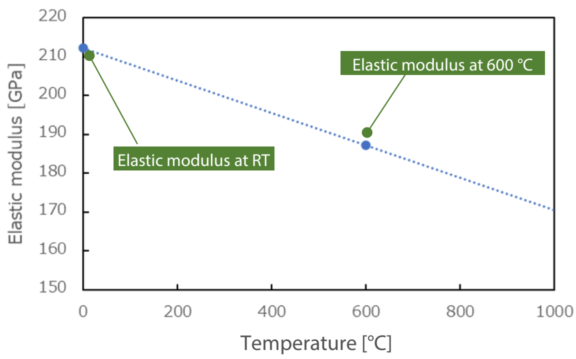


Fig. 5 Relationship between Elastic Modulus and Temperature

■ High-Temperature Ultrasonic Fatigue Tests of Inconel 718

Table 2 shows the test conditions. The test was performed using intermittent operation with repeated excitation and stoppage, so that the test temperature did not exceed 606 °C, which is within 1 % of the set temperature. Fig. 6 shows the temperature variation of the test specimen while intermittent operation was performed. Fig. 7 shows the S-N curve of Inconel 718 at 600 °C. It can be seen that fracture occurred between 10^6 and 10^9 cycles under these loading conditions. Fig. 8 shows a test specimen after fracture.

Table 2 Test Conditions

Loading Stress [MPa]	:	500, 550, 570, 610, 650, 700, 750
Test Temperature [°C]	:	600
Stress Ratio	:	0
Maximum Number of Cycles	:	1×10^9
Other	:	Use of intermittent operation

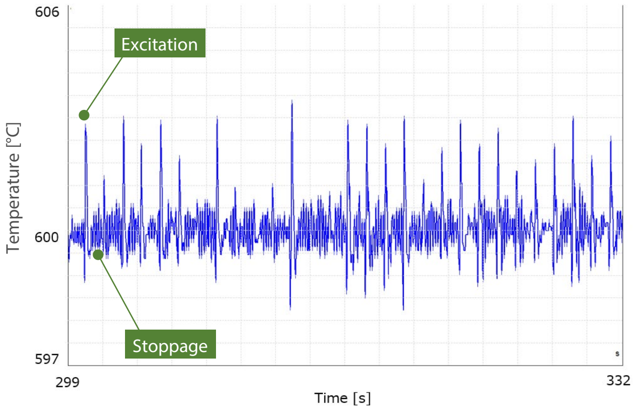


Fig. 6 Temperature Variation during Use of Intermittent Operation
(Loading Stress: 750 MPa, Intermittent Operation:
Excitation 110 ms/Stoppage 1000 ms)

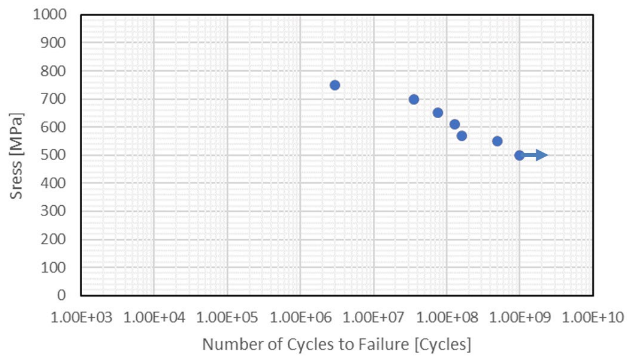


Fig. 7 S-N Curve

Fig. 8 Test Specimen after Fracture

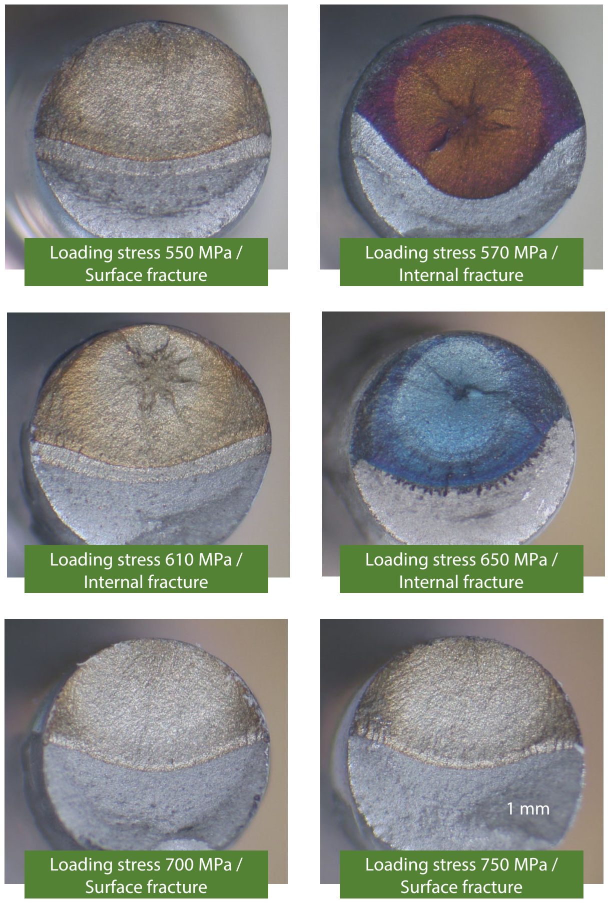


Fig. 9 Fracture Surfaces of Test Specimens after the Tests

■ Observation of Fracture Surface

Fig. 9 shows fracture surfaces of test specimens after testing, obtained from an optical microscope. In the test results, internal fractures that originated from internal inclusions were observed under loading stresses of 570, 610, and 650 MPa. Under loading stresses of 550, 700, and 750 MPa, surface fracture occurred with defects on the surface initiating the fracture. Of these, observation images and element mapping images were obtained using the EPMA-8050G for the fracture surfaces at load stresses of 570 MPa and 650 MPa.

Fig. 10 shows a fracture surface observation under a loading stress of 570 MPa. A COMPO image is an image taken using a backscattered electron detector, and mainly show differences in average atomic number and the effect of slight unevenness as shading. A TOPO image is also an image obtained using a backscattered electron detector, and in particular it clearly shows unevenness. An SE image is an image obtained using a secondary electron detector, and it shows the fine surface shape. The length of inclusions was about 20 µm. Also, from the results of elemental mapping analysis it was found that the inclusion that was the origin of fracture was a compound containing N and Ti.

Fig. 11 shows the results of fracture surface observation under a loading stress of 650 MPa. The length of inclusions was about 20 µm. Likewise, from the results of elemental mapping analysis it was found that the inclusion that was the origin of fracture was a compound containing Ti, Nb, and O.

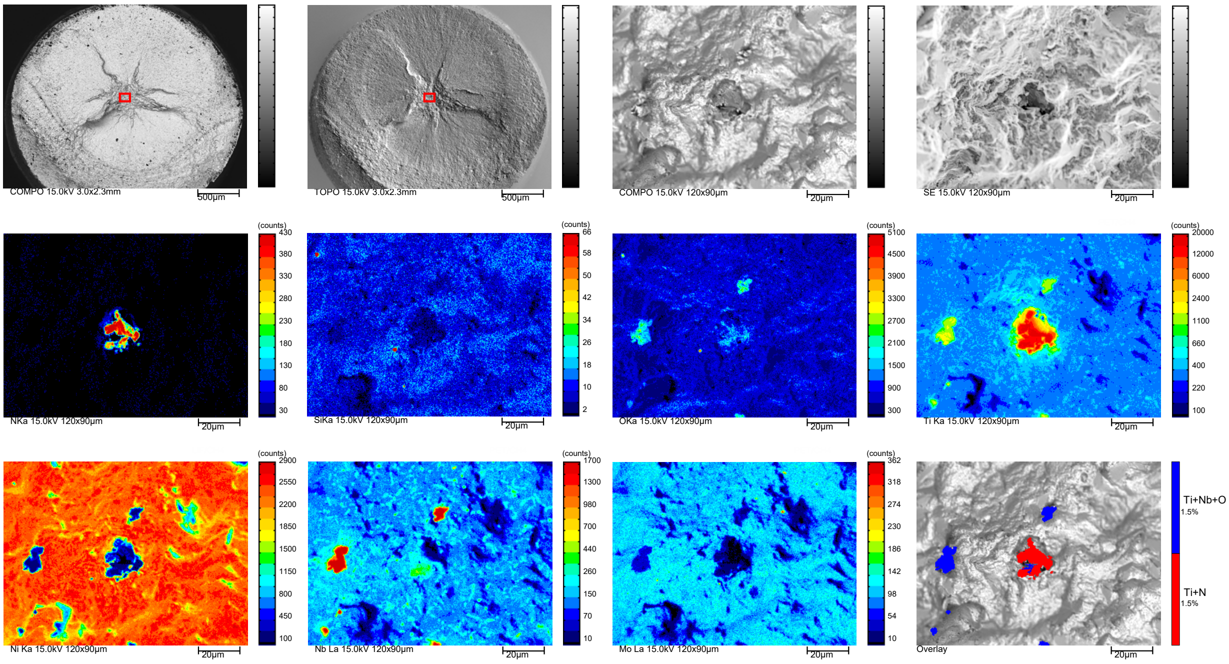


Fig. 10 Observation of the Fracture Surface under a Loading Stress of 570 MPa

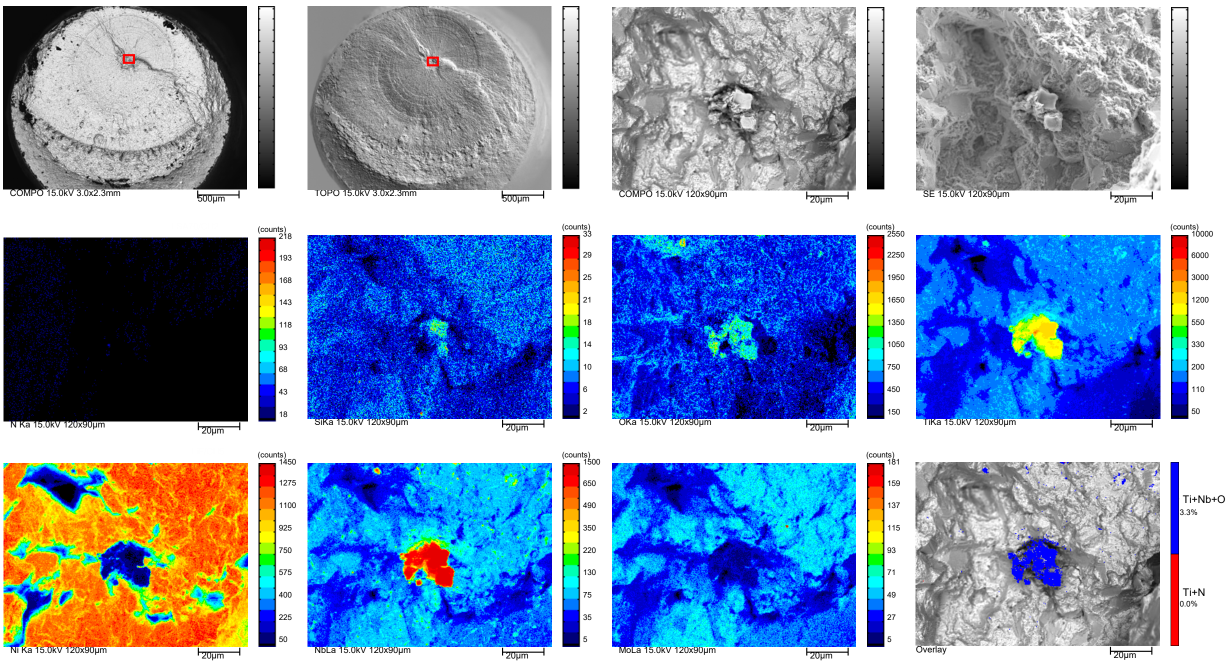


Fig. 11 Observation of the Fracture Surface under a Loading Stress of 650 MPa

■ Conclusion

Gigacycle fatigue tests were performed on Inconel 718 at 600 °C, using the USF-2000A ultrasonic fatigue testing system. Good results were obtained since the number of cycles to fractures fell in the range 10^6 to 10^9 for their respective loading conditions. The EPMA-8050G electron probe microanalyzer was used to perform elemental mapping analysis of fractures originating from inclusions, and the elements of the inclusions were identified.

References

1) FURUYA, Yoshiyuki, et al., "Development of High-Temperature Ultrasonic Fatigue Testing System," Transactions of the Japan Society of Mechanical Engineers (Series A), Vol. 78, No. 789 (2012-5)

Note: The data in this Application News was obtained under the technical guidance of the National Institute for Materials Science.

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