TECHNICAL SPOTLIGHT

ULTRASONIC FATIGUE TESTING FOR ADDITIVELY MANUFACTURED METAL ALLOYS

Compared with traditional fatigue testing, the ultrasonic method achieves much speedier results along with the ability to run extremely high test cycles in a reasonable time frame.

Fatigue testing that employs sample resonance at ultrasonic frequencies is a relatively underutilized technique that is attracting increased interest as a tool to rapidly assess the suitability of alloys for 3D printing. This testing method is especially useful for applications in aerospace, automotive, medical device, and other industries that require high reliability and extremely long performance life. Compared with conventional fatigue tests, ultrasonic testing provides both faster test speeds and the unique ability to test to extremely high cycle numbers in a practical time frame. Very high cycle fatigue (VHCF) testing can reveal material failure modes that would remain undetected under lower cycle fatigue test conditions. Gigacycle fatigue tests, which would take years using traditional test methods, can be performed in about six days with ultrasonic testing, as shown in Fig. 1. This article provides a simple introduction to ultrasonic fatigue testing along with examples of its utility in the characterization of metals including 3D-printed alloys.

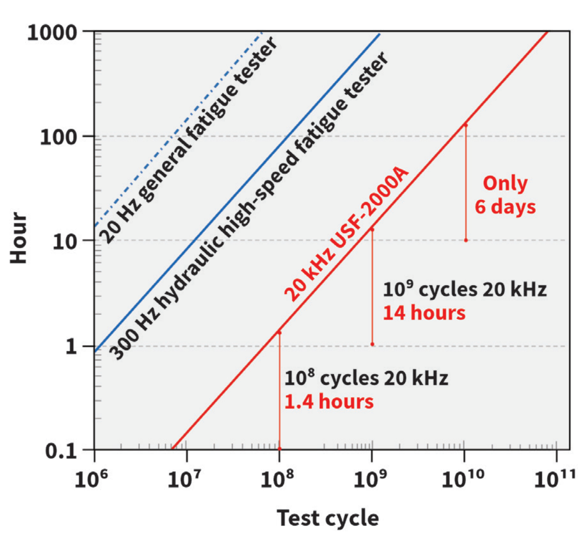

Fig. 1 — Gigacycle fatigue tests that require years of testing using conventional techniques only take about six days with ultrasonic testing.

TESTING BASICS

Fatigue testing involves the periodic stressing of materials below their yield strength to produce plots of applied stress versus the number of test cycles to failure. These S-N plots are used to estimate the expected lifetime of materials for intended design applications.

With traditional fatigue instrumentation, samples are stressed by cyclic external loads generated by a servo-hydraulic or electromechanical mechanism and easily measured with a load cell. Uniaxial fatigue testing methods are well established and thoroughly documented in ASTM publications such as STP 566-EB Handbook of Fatigue Testing, as well as ASTM standards E466-21 and E606, which describe force-controlled and strain-controlled procedures, respectively. ASTM standard E467 describes procedures for dynamic load verification.

Conventional fatigue machines can generate maximum cycle frequencies of about 100 Hz. Consequently, fatigue tests are typically restricted to a

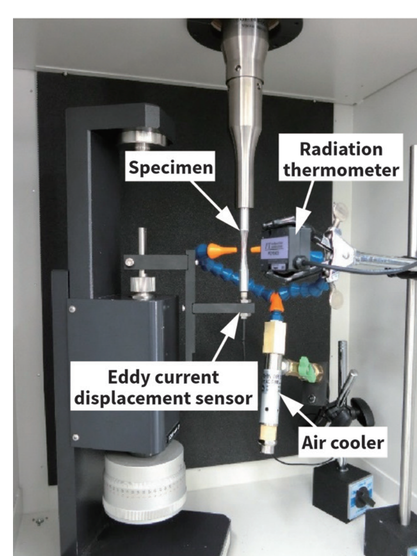

Fig. 2 — Shimadzu USF-2000A ultrasonic fatigue testing system.

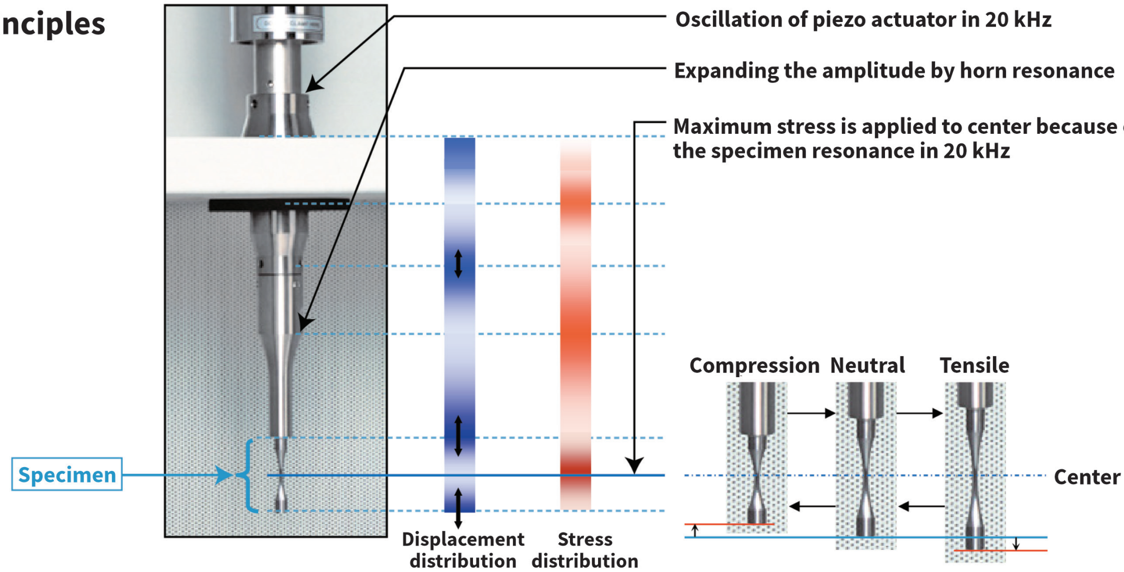

Fig. 3 — Illustration of the principles of a piezoelectric oscillator as wave vibrations move through a sample.

maximum of 10^6 or 10^7 cycles. However, many applications require component fatigue life in excess of 10^7 cycles. Testing in the very high cycle regime in excess of 10^7 cycles has shown that failure can initiate due to internal inclusions rather than surface defects commonly observed in lower cycle testing.

The basic components of an ultrasonic fatigue system are shown in Fig. 2.

A piezoelectric oscillator operating at 20 kHz is connected to a booster and amplification horn, which magnify the displacement of the oscillator. One end of the sample is connected to the horn while the other end is free to oscillate. A longitudinal wave vibration travels through the sample, which then stretches and compresses in resonance with the oscillator. For a resonating sample, maximum displacement occurs at the sample ends while maximum stress occurs at the sample midpoint, as shown in Fig. 3. The amplitude of the displacement is controlled by the power input to the piezoelectric oscillator. The load is not measured directly. System software allows stress to be calculated from sample dimensions and displacement of the free edge of the sample, which is measured using a noncontact eddy current displacement sensor.

The ultrasonic fatigue test can be designed to exert a mean stress on the sample by attaching the entire acoustic wave train to a universal testing machine (UTM) and connecting the sample to a second horn, which is fixed to the base of the UTM frame (Figs. 4 and 5). In this case, the sample displacement used to calculate the sample stress is measured using a strain gauge attached to the sample, as there is no oscillating free end to observe.

The sample shape and length are chosen to allow resonance at 20 kHz. Tapered cylindrical, rod, or notched type samples are used. System software enables the correct sample length for resonance at 20 kHz to be calculated from inputs of the test material's density and Young's modulus.

Fig. 4 — External view of the mean stress loading jig.

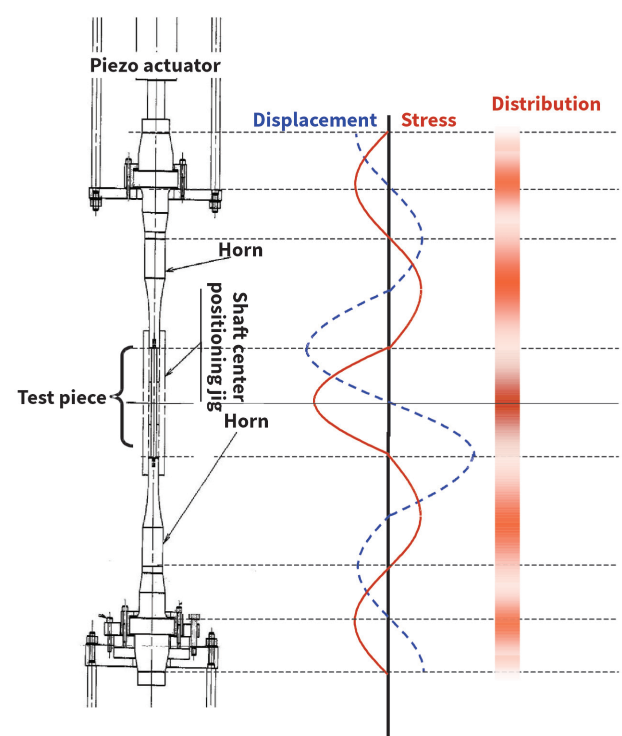

Fig. 5 — The acoustic wave train can be mounted to a universal test machine with the sample connected to a second horn at the base of the frame to apply a mean stress.

The technique is limited to materials that can resonate at 20 kHz without excessive heating. Consequently, this method has been primarily used to test metal samples, although recent studies have successfully employed the technique to test carbon fiber reinforced plastics[1]. To prevent excessive heating of samples, the system is configured with a forced-air cooling mechanism. In addition, the computer control system allows the oscillations to be regularly halted during the experiment to let the sample cool during the test. During testing, sample temperature is monitored using a radiative temperature measuring device.

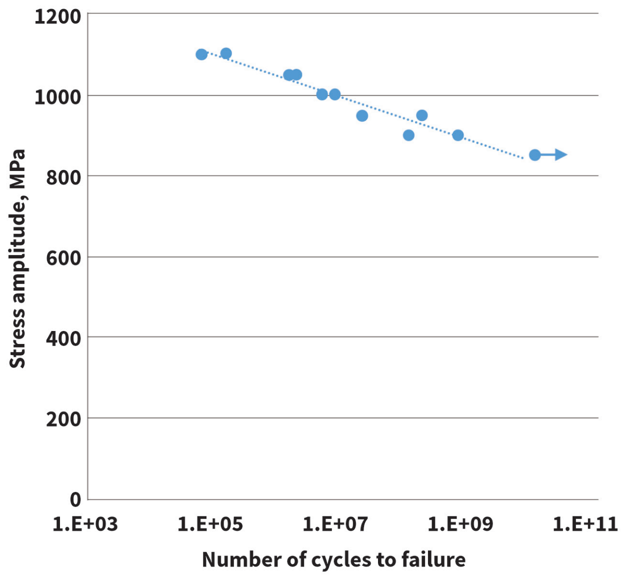

Fig. 6 — S-N curve for SNCM439 steel sample.

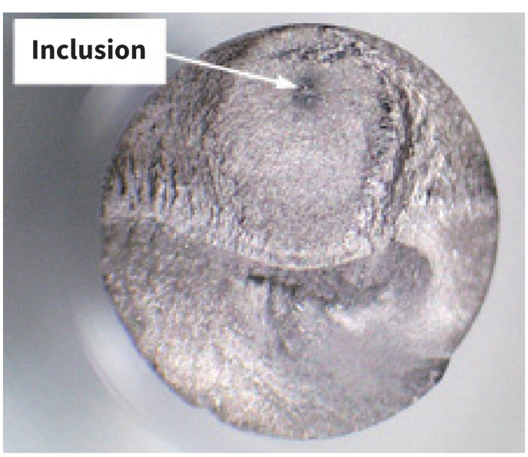

Fig. 7 — Fracture surface of SNCM439 sample.

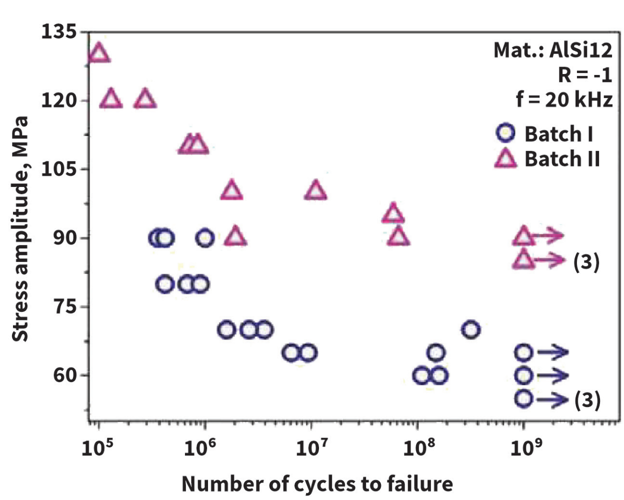

Fig. 8 — Two batches of AlSi12 alloy samples tested to failure. Batch II has base plate heating, while Batch I does not.

A more thorough description of the basics of ultrasonic fatigue testing may be found in the *ASM Handbook* published in 2000[2]. In 2017, The Japan Welding Engineering Society published a standard test method for ultrasonic fatigue testing of metals (WES 1112:2017), which describes the theory and testing procedures in detail[3].

EXAMPLES

To demonstrate the technique, the staff of the Global Applications Development Laboratory of Shimadzu Corporation in Kyoto, Japan, tested SNCM439 steel according to WES 1112:2017 using a Shimadzu USF-2000A system[4,5]. Intermittent operation and forced-air cooling were employed to maintain the sample temperature of 30°C or less as mandated by the standard.

Figure 6 shows how fatigue failure occurred at 10^8 to 10^9 cycles for low-stress magnitudes. Figure 7 shows an optical micrograph of the fracture surface of an SNCM439 sample, indicating that failure initiated at the site of an inclusion.

These data show the importance of fatigue testing at 10^7 cycles and beyond for materials intended for long-lifetime, high-reliability applications. Such testing can reveal failure mechanisms due to internal defects that may go undetected with lower cycle testing. Therefore, ultrasonic fatigue testing can be a powerful technique to characterize alloys intended for additive manufacturing (AM) applications where the effects of AM process parameters on internal microstructure and material performance are not fully understood.

An example of how AM processing parameters can affect VHCF performance is shown in Fig. 8. AlSi12 alloy samples were manufactured using selective laser melting with and without heating of the base[6]. Both samples failed beyond 10^7 cycles. Base plate heating (Batch II) resulted in significantly higher fatigue strength due to a reduction in gas pore size.

Additional examples of ultrasonic fatigue testing of AM materials may be found in the review prepared by Andrea Tridello and Davide Paolino[7]. A comprehensive AM VHCF review article was authored recently by Maryam Avateffazeli and Meysam Haghshenas[8].

ASTM Committee E08 has established a group to discuss the nuances of this technique and develop a best practices guide[9]. **~AM&P**

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