

Very High Cycle Fatigue of Cast Aluminum Alloys under Variable Humidity Levels

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ABSTRACT

Ultrasonic fatigue tests (testing frequency around 20 kHz) have been conducted on four different cast aluminum alloys each with a distinct composition, heat treatment, and microstructure. Tests were performed in dry air, laboratory air and submerged in water. For some alloys, the ultrasonic fatigue lives were dramatically affected by the environment humidity. The effects of different factors like material composition, yield strength, secondary dendrite arm spacing and porosity were investigated; it was concluded that the material strength may be the key factor influencing the environmental humidity effect in ultrasonic fatigue testing. Further investigation on the effect of chemical composition, especially copper content, is needed.

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INTRODUCTION

Some automotive components like engine blocks and cylinder heads experience more than 10^8 fatigue cycles during their expected service life. Fatigue tests, however, are usually limited to 10^7 cycles due to cost and time constraints. In recent decades, the ultrasonic fatigue testing technique has attracted more and more attention because of its high testing frequency (around 20 kHz). A remarkable reduction in testing time can be achieved using ultrasonic fatigue test systems for data generation. It is possible to test to 10^9 cycles in only 14 hours under ultrasonic fatigue frequency, while the same test at 75 Hz would run more than 5 months.

Although ultrasonic fatigue testing is very efficient for data generation, the fatigue life at such high frequencies is not always equivalent to the fatigue life obtained by traditional servo-hydraulic testing systems [1, 2, 3, 4, 5, 6, 7, 8, 9]. Caton *et al.* [6] observed no influence of loading frequency for the cast aluminum E319 alloy; Holper *et al.* [7] also found no strain rate influence under vacuum for the 2024 and 7075 aluminum alloys. Engler-Pinto *et al.* [1, 2], however, have conducted ultrasonic and conventional fatigue tests on different cast aluminum alloys and found out that ultrasonic fatigue lives were sometimes higher than the fatigue lives obtained from conventional servo-hydraulic fatigue tests; they also reported that ultrasonic fatigue testing of samples submerged in water consistently resulted in fatigue lives that were similar to conventional fatigue tests performed in ambient (laboratory) air. Zhu *et al.* [3] also obtained similar results for the E319 cast aluminum alloy: longer ultrasonic fatigue life in lab air compared to ultrasonic fatigue tests submerged in water. These findings indicate that the environment humidity plays

an important role on the fatigue behavior of some cast aluminum alloys. The main objective of this paper is to investigate the effect of humidity in ultrasonic fatigue testing.

MATERIALS AND EXPERIMENTAL PROCEDURES

The chemical composition of the four cast aluminum alloys investigated in the present paper is given in Table 1. Ultrasonic fatigue tests were conducted using a fatigue test machine manufactured by the University of BOKU, Vienna, Austria [4] as shown in Figure 1(a). Ultrasonic fatigue testing is conducted by generating a sinusoidal wave using an ultrasonic transducer, which is amplified and injected into the specimen. The geometry of the test fixtures need to be optimized according to the physical properties of the specimen (density and modulus of elasticity). If the excited signal frequency is equal to the resonance frequency of the specimen, the injected and reflected waves will superimpose to form a resonance vibration, leading to a cyclic loading with maximum strain amplitude in the center of specimen. For a more detailed explanation of the ultrasonic testing methodology, the reader is referred to previous publications [4, 5]. Small strains amplitudes are chosen in order to avoid the development of significant cyclic plastic strains; in this manner, the resultant stress amplitude can be calculated elastically using Hooke's law. Ultrasonic loading was applied in well controlled pulses (200 ms on / 2000 ms off) to keep the specimen temperature below 25°C.

Table 1. Chemical composition in weight percentage.

Alloy	Al	Si	Cu	Mg	Fe	Ti	Mn	Sr
C448	Bal	10.9	<0.01	0.17	0.12	---	---	---
E319	Bal	7.4	3.3	0.22	0.78	0.13	0.24	0.03
AS7GU	Bal	6.9	0.47	0.37	0.14	0.14	0.06	0.03
A356	Bal	7.1	<0.01	0.36	0.10	0.12	0.03	0.025

A special device was built to control the humidity level for the ultrasonic fatigue tests, as shown in Figure 1(b). Dry air (relative humidity < 1%) and fully saturated air (relative humidity > 99%) was simultaneously generated by the humidity controller. Using a combination of dry air and saturated air, any humidity level can be achieved and injected into the chamber attached to the ultrasonic fatigue test machine shown in Figure 1(a). To avoid affecting the resonance vibration of the specimen, the chamber is installed on the neutral node point of the lambda rod.

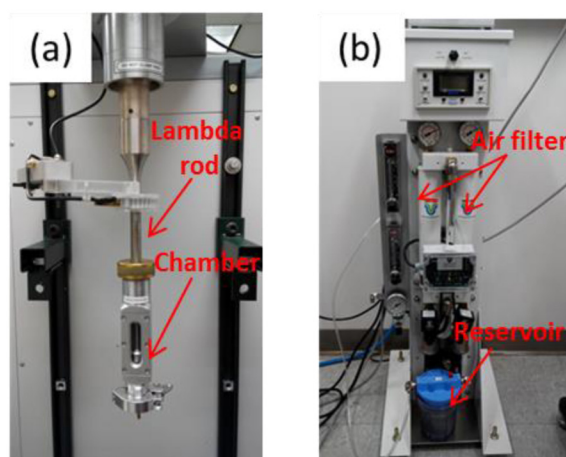


Figure 1. (a) Ultrasonic fatigue testing frame, (b) Humidity generator.

RESULTS AND DISCUSSION

The aluminum alloys investigated were obtained from different sources and with different heat treatments, which resulted in diverse properties and microstructures, as summarized in Table 2. The average tensile properties reported in Table 2 were obtained from tensile tests using at least 6 specimens: yield strength at 0.2% plastic strain (YS), ultimate tensile strength (UTS) and plastic elongation. The secondary dendritic arm space (SDAS) for each tested alloy was also evaluated and is reported in table 2 (minimum of 100 measurements over a 500mm² area using image analyzer software).

Although a comprehensive evaluation of the pore sizes for all alloys investigated was not carried out, it was possible to perform a qualitative assessment of the porosity present in the different alloys based on the fractographic analyses conducted on failed specimens. In this way, the qualitative values reported for porosity in Table 2 correspond to:

1. “**Very low**”: no fatigue cracks initiated from pores - pore sizes usually smaller than 100 μm ;
2. “**Low**”: some cracks initiated from pores - pore sizes in the 100-300 μm range;
3. “**Medium**”: most cracks initiated from pores - pore sizes in the 300-700 μm range;
4. “**High**”: all cracks initiated from pores - pore sizes larger than 700 μm .

Also reported in Table 2 is the “ultrasonic fatigue ratio” (UFR), which is defined as the ratio between the fatigue strengths obtained in ultrasonic fatigue in dry air and submerged in water. The UFR is therefore a measurement of the sensitivity of the alloy to the environment humidity when tested in ultrasonic fatigue (a UFR close to unity means that the ultrasonic fatigue behavior of the alloy is not affected by the humidity).

The stress-life (S-N) curves obtained from ultrasonic fatigue tests carried out in dry air (or lab air, humidity level around 20%, when dry air tests were not available) and submerged in water are presented in Figures 2, 3, 4, 5, 6, 7, 8 for all the alloys investigated. Specimens that did not fail (runouts) are indicated by arrows. The plotted lines represent the median S-N Curves according to the Random Fatigue Limit (RFL) model [1].

It is clear from Figure 2 that the C448-T5 alloy is essentially insensitive to humidity and presents the same ultrasonic fatigue behavior in dry air and submerged in water (UFR=1). The alloys A356-T6a (UFR=1.7) and A356-T6b (UFR=1.5), Figures 7 and 8, respectively, exhibit the highest sensitivity to humidity, as the ultrasonic fatigue lives are drastically reduced when the specimens are tested under water. It is worth noting that these alloys are heat treated to the T6 (maximum strength) condition.

Some researchers [10, 11, 12] reported that porosity is a critical feature affecting the fatigue behavior of cast alloys. In fact, when present above a certain critical size, these casting pores generally act as preferred fatigue crack initiation sites. A comprehensive fractographic evaluation using scanning electron microscopy (SEM) was performed on all specimens tested; typical fracture surfaces are presented in Figures 9, 10, 11, 12, 13 illustrating the different types of pores present in these alloys.

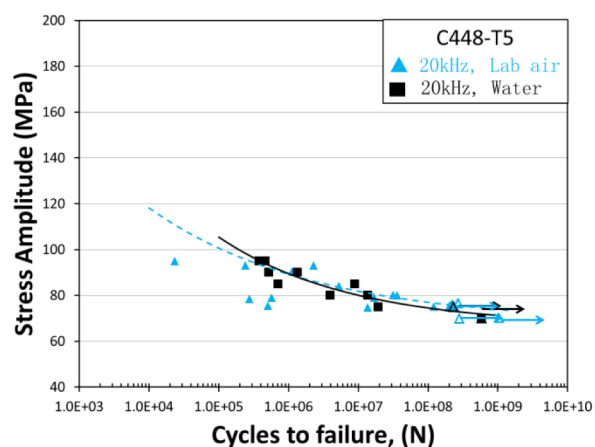


Figure 2. C448-T5 ultrasonic fatigue test results in lab air and submerged in water.