

Effect of Humidity on the Very High Cycle Fatigue Behavior of a Cast Aluminum Alloy

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ABSTRACT

In this paper, fatigue tests on a cast aluminum alloy (AS7GU-T64) were performed under different frequencies and humidity levels. Tests conducted under conventional frequency in laboratory air have been compared to tests conducted under ultrasonic frequency in dry air, saturated humidity and in distilled water. It was observed that the highest and lowest fatigue lives correspond to ultrasonic fatigue tests in dry air and in distilled water, respectively. Unlike specimens tested at conventional frequency, all of the specimens tested at ultrasonic frequency presented a large amount of slip facets on the fatigue crack propagation fracture surface.

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INTRODUCTION

Some automotive components, like engine blocks and cylinder heads, experience more than 10^8 alternating stress cycles during their service life. However, conventional fatigue testing usually limited to 10^7 alternating stress cycles since it is quite expensive to complete tests with 10^8 cycles or more at conventional fatigue testing frequencies (20-200 Hz). In order to investigate the fatigue behavior of materials for cycles greater than 10^7 , ultrasonic fatigue testing technique is usually applied [1, 2, 3]. Reasonable testing time for cycles greater than 10^7 can be achieved using ultrasonic fatigue testing, which runs at approximately 20 kHz. With this testing technique, the fatigue stress-life (S-N curves) data generation can be greatly accelerated.

One of the problems with using the ultrasonic fatigue technique is that for some materials the fatigue life obtained under very high frequency does not correlate well with the fatigue life at conventional frequencies [4, 9]. Engler-Pinto *et al.* [4] found out that for a cast aluminum alloy, ultrasonic fatigue tests in air resulted in much longer lives than fatigue tests in air conducted at 40 Hz; the same paper reported that ultrasonic fatigue tests conducted under water resulted in fatigue lives very similar to the ones obtained at conventional frequencies in air. It was concluded that the environment humidity level has a great impact on the fatigue life obtained at ultrasonic frequency.

Weir, Wei and Stanzl-Tschegg [6,7,8, 18] have shown that the crack growth rate can be accelerated in the presence of humidity. The accelerated crack growth observed under high humidity has been attributed to hydrogen embrittlement [8]. Therefore, the ultrasonic fatigue life is affected by the humidity level in the testing environment: a higher humidity results in lower fatigue life. Some other researchers have reported the presence of "facet planes" on the fracture surfaces of samples tested under ultrasonic and conventional frequencies [9,10,11]. Zhu [9] observed facets in specimens of cast 319 aluminum alloy under ultrasonic frequency, which only occurred at elevated temperature. Wang [10] reported facets on the fracture surfaces of specimens from the A356 alloy treated by hot isostatic pressure (HIP) under conventional frequency. Miao [11] also observed similar facets in specimens from a nickel based super alloy under ultrasonic frequency. Zhu [9] and Wang [10] described these facets as slip bands; Miao [11] also reported that the facets were slip bands that formed near twin boundaries.

In this study, in order to investigate the effect of humidity on the ultrasonic fatigue properties, ultrasonic fatigue tests were carried out in different conditions: dry air, saturated humidity and submerged in distilled water. For comparison, conventional fatigue tests in laboratory air (humidity of about 20%) were also conducted. The morphology of the fracture surfaces was characterized using scanning

electron microscopy (SEM). For selected specimens, the percentage of facets present on the fracture surface was also evaluated and the mechanisms for the formation of the facets are discussed.

MATERIALS AND EXPERIMENTAL PROCEDURES

The cast aluminum alloy in this study is designated as AS7GU and the measured chemical composition is given in Table I. It is a primary cast aluminum alloy derived from the A356 alloy with an addition of 0.5% copper (Cu) to increase strength at elevated temperature. This alloy is usually used in high performance engine cylinder heads. The samples used in the present investigation were cut from real cylinder heads, as illustrated in Figure 1(a). Figure 1(b) shows the typical microstructure of the material, which consists of primary α -aluminum dendrites and Al-Si eutectic.

Table I. Chemical composition in weight percentage.

Al	Si	Cu	Mg	Fe	Ti	Mn	Sr
Bal	7.04	0.48	0.36	0.11	0.14	0.06	0.03

Table II. Mechanical properties of AS7GU alloy

Modulus of elasticity (GPa)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)	SDAS (μm)
77.8	207	290	8.8	23

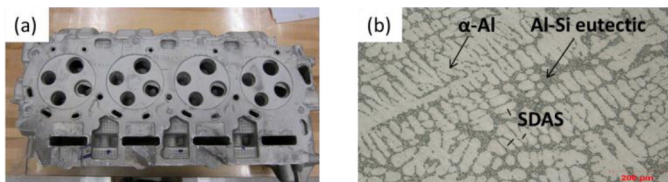


Figure 1. (a) Cylinder head, (b) Microstructure of AS7GU cast aluminum alloy.

These cylinder heads were subjected to a T64 treatment which corresponds to an under-peak aged condition. The tensile properties at room temperature are summarized in Table II. The modulus of elasticity was evaluated for all specimens tested under the servo-hydraulic test system by cycling at 1Hz and ± 30 MPa for 10 cycles; the average value for all samples is reported in Table II. The secondary dendrite arm spacing (SDAS), which is an important feature for cast aluminum alloys, is also reported in Table II.

SDAS is governed by the solidification rate; in general, higher solidification rate results in finer SDAS [12] and better mechanical properties. The SDAS was measured using Image Pro software on a 500mm² finely polished area (up to 1 μm oxide aluminum powder). Over 100 measurements were made for each average value reported in Table II.

All fatigue specimens were machined using low stress turning and longitudinally polished with 600 grit sand paper as shown in Figure 2. Ultrasonic fatigue testing was conducted using an ultrasonic fatigue testing machine manufactured by the University of BOKU, Vienna, Austria [17], as shown in Figure 3(a). A sinusoidal wave is

injected from ultrasonic transducer into one end of the ultrasonic lambda rod with the velocity determined by the material properties (density, modulus of elasticity and the shape of the component). The waves enter the specimen and are reflected from the other end of the specimen. If the excited signal frequency is equal to the resonant frequency of the specimen, the injected and reflected waves will superimpose to form a resonance vibration. More detail about ultrasonic fatigue testing can be found [2, 17]. All specimens were under fully reversed tension compression loading condition ($R=-1$). Ultrasonic loading was applied in well controlled pluses (200ms on/2000ms off) to keep the specimen temperature below 25°C during the ultrasonic fatigue testing.

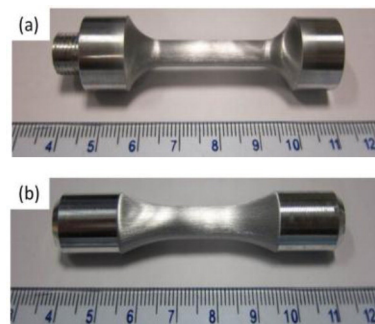


Figure 2. Ultrasonic (a) and conventional (b) fatigue specimen.

In order to obtain different relative humidity environments, a humidity chamber, Figure 3, was specially designed and manufactured. The device shown in Figure 3(b) allows to achieve any desired humidity level in the chamber by mixing different volume ratios of dry and fully saturated air, which continuously flow into the chamber. To avoid affecting the resonant vibration of the specimen, the chamber was installed on the node point of the lambda rod. In the present investigation, only tests performed under dry air and saturated humidity are reported.

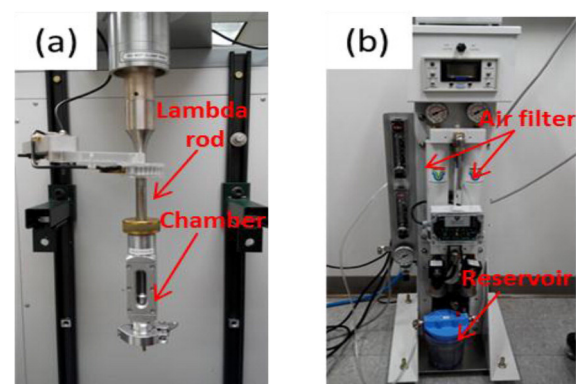


Figure 3. (a) Ultrasonic fatigue test frame (b) Humidity generator.

RESULTS AND DISCUSSION

Ultrasonic fatigue testing was carried out in various environments with different RH (relative humidity) levels: dry air ($RH < 1\%$), saturated humidity ($RH > 99\%$) and submerged in distilled water. The room temperature S-N curves at 20 kHz for these different humidity

levels are shown in Figure 4. Specimens that did not fail (run-outs) are indicated by arrows pointing to the right. The plotted lines represent the median S-N curves which were calculated according to the random fatigue limit (RFL) model [4, 15].

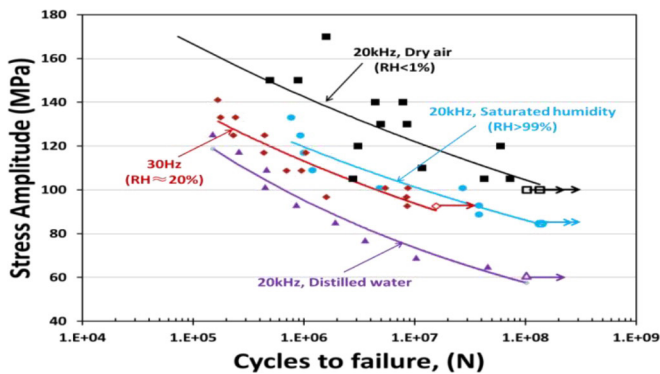


Figure 4. Ultrasonic and conventional fatigue testing results of AS7GU cast aluminum alloy.

In ultrasonic fatigue testing, tests performed in dry air resulted in the highest fatigue life and tests in distilled water resulted in the lowest fatigue life. This seems to indicate that humidity, or the water vapor pressure, is detrimental to the fatigue properties for this alloy. These results are consistent with recent work done by Engler-Pinto [4], Zhu [5] and Stanzl-Tschegg [1] who also observed that increasing the humidity level resulted in decreased fatigue life for cast aluminum alloys. It is also interesting to note that the fatigue life of samples tested under conventional frequency (30 Hz) in ambient air lies between ultrasonic fatigue lives obtained in saturated humidity and distilled water.

For this study, all specimens were excised from the deck face of a high performance cylinder head, which contains very low levels of casting defects like porosity, oxides and non-metallic inclusions, due to the fast solidification rate achieved during casting. In the absence of such defects, which would be potential crack initiation sites, all fatigue cracks in this study initiated from the specimen surface through a mechanism of slip facet formation, as shown in Figure 5.

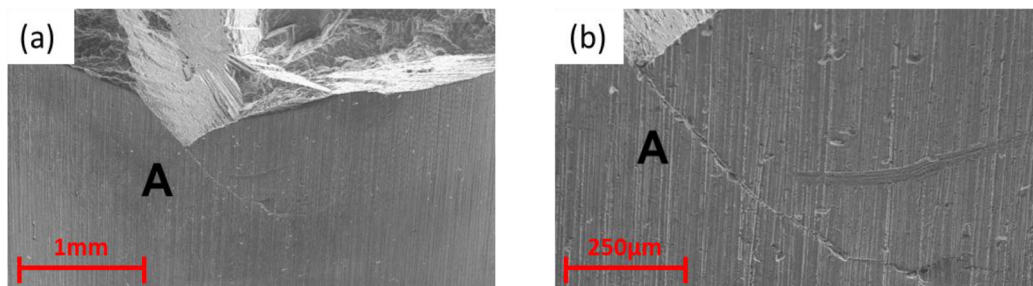


Figure 5. (a) SEM picture of ultrasonic fatigue crack initiation site (140MPa in dry air), (b) Magnified view of A.

Figure 6 shows the fracture surface of selected specimens tested at ultrasonic frequency under different environments. A distinct feature is the presence of a relatively large amount of facets on the fatigue crack propagation path, especially for the specimens tested in dry air, Figures 6(a) and 6(b). In fact, the amount of facets decreased significantly for tests performed under distilled water, Figures 6(e) and 6(f). Specimens tested at conventional frequency (30 Hz) and 20% humidity showed very minimal facets, which could only be observed at the initiation sites, as illustrated in Figure 7. Even for the specimens tested at ultrasonic frequency, the facets tended to locate closer to the fatigue crack initiation site, indicating that these facets were all formed during the slow crack propagation stage.

In order to better understand the nature of these facets, some specimens that did not fully separate during the fatigue test have been sectioned and polished to expose the fatigue crack path, as shown in Figure 8. As shown in Figures 5, 6, 7, 8, the facets observed on the fracture surfaces, for both ultrasonic and conventional frequencies, form at an angle of approximately 45° to the loading direction, which correspond to the maximum shear stress direction.

Zhu [5], Miao [11, 13] and Tiryakioglu [14] have studied the mechanisms of facet formation in different materials and reported that these facets could be originated by slip bands. In order to examine the nature of the facets observed in the present investigation, Electron Backscattered Diffraction (EBSD) analysis was used and the results are shown in Figure 9. The pictures from Figure 9 (a) and (c) are SEM pictures and the facets are indicated by red arrows. Figure 9 (b) and (d) are the corresponding inverse pole maps obtained from the EBSD analysis; different colors indicate different crystallographic orientations (different grains). It is observed from Figure 9 that the facets are always located within grains, which discards the hypothesis of the facets being twin boundaries. In fact, Figure 9 (c) and (d) show a slip facet that crosses an entire grain; the fatigue crack then continued to propagate along the grain boundary (propagation was left to right in that picture).

It has been concluded that these observed facets are actually slip facets, which develop on grains that are favorably oriented relatively to the loading direction when the fatigue crack propagation is below a certain threshold value.