Ultrasonic fatigue testing device under biaxial bending

C. Brugger, T. Palin-Luc
Arts et Metiers ParisTech, I2M, CNRS, Universite de Bordeaux
Esplanade des Arts et Métiers, 33405 Talence, France
charles.brugger@ensam.eu, https://orcid.org/0000-0001-9072-7745
thierry.palin-luc@ensam.eu

P. Osmond, M. Blanc
PSA Peugeot Citroën

ABSTRACT. A new fatigue testing device has been developed to test specimens under biaxial loading at 20 kHz. A flat smooth specimen with a disc geometry is placed on a torus frame and cyclically loaded at the center of its upper face. Disc bending generates a biaxial proportional stress state at the center of the lower face. Any positive loading ratio can be applied. A cast aluminum alloy (used to produce cylinder heads) has been tested under biaxial bending using this device in order to determine its fatigue strength at 10^9 cycles under high hydrostatic pressure. Self-heating is moderate but macroscopic fatigue cracks after testing are very long. First results in VHCF regime are consistent with literature results obtained under similar stress state but in HCF regime and at 20 Hz.

KEYWORDS. Gigacycle fatigue; Biaxial loading; Bending; Cast aluminum alloy; Ultrasonic testing machine.

INTRODUCTION

Many components in several industries are loaded in VHCF regime, either at high frequency (wheels of high speed trains, blades in aircraft turbojet engines, etc.) [1] or at low frequency during decades (artificial heart, mooring chains for off-shore petroleum platforms, etc.) [2, 3]. Testing specimens up to 10^9 or 10^{10} cycles in a realistic time requires to use a very high loading frequency (20 or 30 kHz). Several devices using the ultrasonic testing technique have been developed all over the world since Mason's work in the 1950's [4]. A significant effort in this field has been done since the end of the last century [1, 5]. Specimens can be tested under tension (R=-1 or R>0), torsion (R=-1 or R>0) or bending (R>0), either at room, low or high temperature, in air or in liquid environment [1-5], but there is no machine for testing specimens under multiaxial loading. However, it is known that during their life many industrial components are submitted to multiaxial loadings that may lead to a number of cycles close to one billion or more. Fatigue cracks may initiate in areas experiencing multiaxial stress states. That is the reason why a new fatigue testing device has been developed to test specimens under biaxial loading at 20 kHz.

After presenting a brief state of the art on ultrasonic fatigue testing machines, the principle of a new biaxial bending device and the associated stress state are presented hereafter. The first results obtained on a cast Al-Si alloy in VHCF regime are then compared with those obtained in literature under similar stress state but in HCF regime and under lower frequency.

STATE OF THE ART: ULTRASONIC TESTING MACHINES

According to the literature, the first ultrasonic fatigue testing device was developed by Mason in the 1950's under fully reversed tension [4, 6]. An interesting review of ultrasonic fatigue testing machines is given by Bathias in [5]. The basic principle of an ultrasonic fatigue testing machine is to apply to a specimen an axial sinusoidal displacement at an ultrasonic frequency (typically 20 kHz). The specimen is designed so that it has a natural frequency (or mode) at this frequency. An ultrasonic fatigue testing machine is made with: (i) a generator applying an electric signal (at 20 kHz) to (ii) a piezoelectric converter that converts the electric signal in a longitudinal vibration at the same frequency, and (iii) a horn for amplifying the vibration finally applied at one end of the specimen. The generator is controlled by a computer so that the resonance of the whole system (piezoelectric converter, horn and specimen) is kept all the test long.
This principle has been used by several authors to design special apparatuses for testing specimens under fully reversed tension. Coupled with electromechanical or servo-hydraulic testing machines, such equipment can be used for gigacycle fatigue tests under tension with several positive R ratios. A machine has been developed for three points bending test with R>0 too [1]. All these machines allow tests on smooth or notched specimens under uniaxial stress state. Some authors [1, 7, 8] have also developed torsion testing machines working like uniaxial ones, by pulse and pause [7, 8] or continuously [9]. Furthermore, the ultrasonic testing technique can be used for testing specimens at room temperature with air cooling if needed, or at high temperature [1, 10], in cryogenic environment [1] or in corrosive liquid environment [2, 3]. But all these testing machines apply a uniaxial loading on the specimen.

ULTRASONIC BIAXIAL BENDING DEVICE

Principle

The new fatigue testing device presented hereafter is designed for testing in bending under ultrasonic frequency a flat smooth specimen with a disc geometry [11]. Its principle is similar to the testing apparatus proposed by Koutiri et al. [12, 13] but this last one was mounted on a servo-hydraulic testing machine working around 20 Hz only. The specimen is placed on a frame with a torus ring, so that the contact zone between the lower face of the disc and the frame is a circle. A load is applied at the center of the upper face using a hemispherical indenter (Figure 1a). Like in a three points bending test, this leads to the bending of the disc.

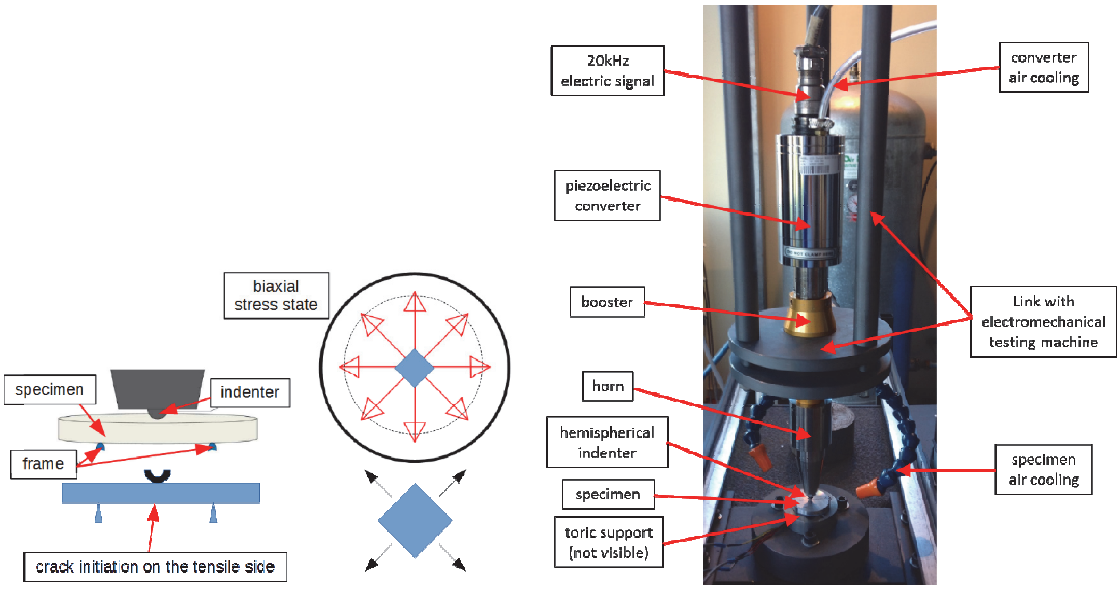

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Figure 1: a) Principle and b) Picture of the ultrasonic biaxial bending device.

Using an electromechanical testing machine and the ultrasonic loading device described in the following paragraph, both a static load and a sinusoidal displacement (at 20 kHz) are applied at the center of the specimen. Under the common assumption that macroscopically the material remains elastic in gigacycle fatigue regime, any positive loading ratio can be applied. In practice, to assure uninterrupted contact between specimen and indenter, loading ratios very close to zero are avoided; R>0.05 are recommended.

The ultrasonic loading device, partly illustrated in Figure 1b, is classic [1]. It consists of a 20 kHz electric generator, a piezoelectric converter, a booster and a horn to amplify the sinusoidal axial displacement like in 3 points ultrasonic bending [1, 5]. In order to apply a non-zero mean load, this device is attached to an electromechanical testing machine using bars and hollowed discs attached to the center of the booster, which is a vibration node. Finally, a servo-control system adjusts in real time the loading frequency to match the natural frequency of the whole device. For that reason, each part (booster, horn and specimen) must be carefully designed, so that their natural frequency for axial displacement matches 20 kHz. The next section details, for some parts, how geometry was determined using FEA modal analysis.

Geometry of the Specimen and Device

First, in order to perform a modal analysis, both the density and the dynamic modulus (at 20 kHz) of the tested material are experimentally measured by using a cylindrical bar as explained in [1] for designing tension compression specimens. The specimen geometry (Figure 2a) is described by only two parameters: diameter and thickness of the disc. These parameters are determined iteratively using a free-free modal analysis computed with a commercial FEA software. The ideal geometry corresponds to a first natural frequency – associated with biaxial bending – equal to 20 kHz. For a given stress state at the center of the lower face, contact forces rapidly increase with thickness. On the other hand, since the hemispherical indenter is located at the center of the upper face, the stress state might be disturbed by the loading if the disc is too thin. For the application described in the next section, a compromise has been found by fixing the thickness equal to 6 mm. The location of the vibration nodes on the specimen gives the radius of the frame ring in order to minimize the relative displacement between the specimen and the frame, then the frictional heating.

Associated Stress State

Theoretically, disc bending generates an equi-biaxial proportional stress state at the center of the specimen's lower face, and stress level is proportional to the center's displacement [9]. Three calibration specimens were instrumented with strain gauge rosettes glued in the center of the lower face. Tests were performed for different amplitudes of the displacement, for a static load assuring a positive load ratio. After measuring strains amplitudes using both a wide band conditioning device (Vishay 2210) and high speed data recorder, stresses amplitudes were computed assuming an isotropic linear elastic behavior of the material (because of testing conditions in the VHCF regime). Since results are almost proportional to the displacement, Table 1 summarizes the results on 3 specimens for a given 10 μm amplitude. Considering the uncertainties related to the experimental measurements (position of the strain gauges, gauge factors, etc.), stress state can be considered equi-biaxial.

1st principal stress amplitude (MPa)	2nd principal stress amplitude (MPa)	Von Mises equivalent stress amplitude (MPa)
27.8	26.2	27.0
26.9	26.6	26.8
28.2	26.5	27.4

Table 1: Stresses at the center of the lower face for a 10 μm amplitude displacement.

APPLICATION TO A CAST AL-SI ALLOY

This ultrasonic biaxial fatigue testing device has been tested and validated on a cast aluminum alloy used to produce cylinder heads and previously investigated by Koutiri et al. [12, 14]. Since cast materials may contain casting defects (porosities, shrinkages, etc.), and because cylinder heads are submitted to high hydrostatic pressure loadings during a very high number of loading cycles, a safe fatigue design requires to determine the fatigue strength of the material under similar stress state in the gigacycle regime.

Material and Specimen

The material is the cast AlSi7Cu05Mg03 T7. Its conventional yield stress is 250 MPa [12, 14]. The specimen geometry is illustrated in Figure 2a. Specimens were machined out of cast cylinder heads. In order to get enough material volume, cores were diminished prior to casting. This allows for microstructure parameters similar to production parts (DAS, porosities, and hardness). The circular ring has a 34 mm diameter.

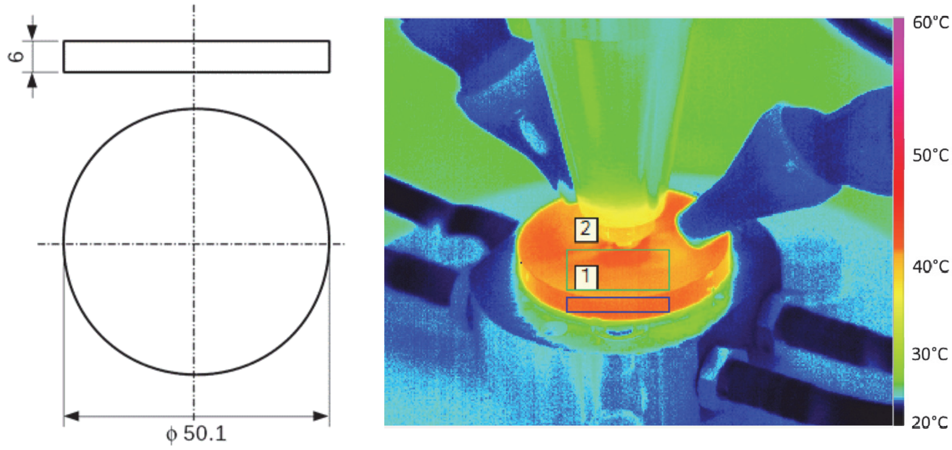

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Figure 2: a) Specimen geometry and b) Temperature measurement by IR camera during ultrasonic fatigue test.

Testing Conditions and Results

Tests are performed in air, at room temperature, for R=0.1 load ratio. Cyclic loading is stopped after 10^9 cycles, or when frequency drops down to 19,500 Hz due to fatigue crack propagation. Both static load and sinusoidal displacement levels were determined using calibration specimens.

Since ultrasonic loading may generate self-heating, specimen cooling is necessary. Dry compressed air is orientated with an air gun towards the upper face (Fig. 1b and 2b). In order to quantify self-heating, surface temperature has been measured during selected tests using an infrared camera FLIR SC 7000 (Fig. 2b). Since no surface was perpendicular to the camera, temperature was averaged on the areas labeled 1 and 2 on Figure 2b. For maximal stresses equal to 130 – 140 – 150 – 160 MPa, the mean temperature stabilizes respectively at 65 – 75 – 80 – 85°C. Such temperatures are negligible compared to metallurgical transformations of the Al alloy.

The first fatigue test results are illustrated in Figure 3. Additional results obtained in HCF regime at 20 Hz for the same material and similar stress state [12, 14] are also presented for comparison purpose.

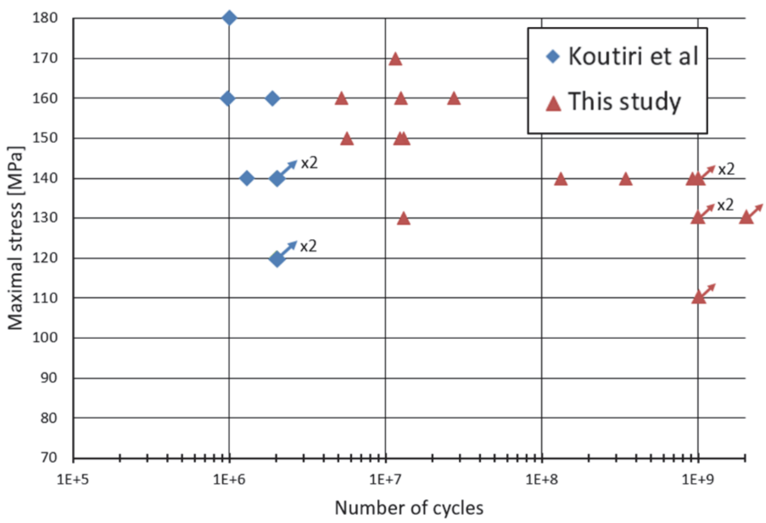

Figure 3: Fatigue test results under biaxial bending: results of this study at 20 kHz in VHCF regime and results from [12, 14] on the same material at 20 Hz in HCF regime.

Discussion

For maximum stress levels equal or lower than 140 MPa, the first results obtained with the new ultrasonic biaxial testing device are in good agreement with the results by Koutiri et al [12, 14]. In our data, there is only one specimen broken very early, for a reason to be clarified. The median fatigue strength at 10^9 cycles is close to 63 MPa (corresponding to a maximal stress equal to 140 MPa).

Figure 4 illustrates, in a Dang-Van diagram [15], both the experimental median fatigue strengths at 2.10^6 cycles obtained by Koutiri [12] on smooth specimens made in the same cast Al alloy and the threshold line identified from torsion (R=-1) and tension (R=-1) data. Furthermore, the loading paths corresponding to existing ultrasonic fatigue testing machines are shown: torsion (R=-1), tension (R=-1), tension or 3 points bending (R>0). The loading path corresponding to the specimens tested at the stress level corresponding to 1.10^9 cycles with the new device presented here is illustrated. It is clear that this device allows questioning the Dang-Van criterion for higher hydrostatic stress states. The same conclusion is valid for the Crossland criterion too [16].

It should be noted that the results obtained for maximum stress levels equal or greater than 150 MPa cannot be directly compared with literature results due to different stop criteria. Indeed, the test results presented in this paper were stopped when the resonance frequency decreased from about 19,900 Hz to 19,500 Hz. Such frequency drop is due to rigidity loss associated to a very large macroscopic fatigue crack propagation. Indeed, macroscopic cracks are either unique or branched but always extended almost to the frame ring when the test stops (Fig. 5). Additional investigations are needed to quantify the number of cycles associated with this propagation, but first observations indicate it might exceed 10^7 cycles. However, one can note that 10^7 cycles represent 1% only of 10^9 cycles.

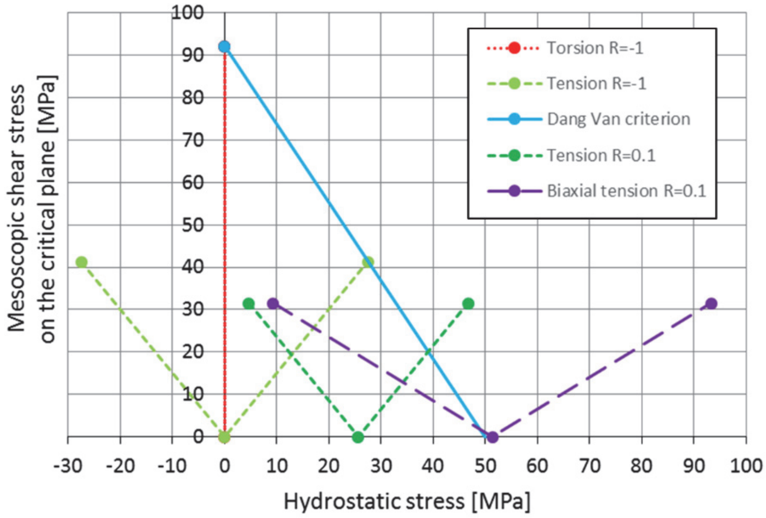

Figure 4: Dang Van diagram for the cast Al-Si alloy: loading paths associated with existing ultrasonic fatigue machines and new ultrasonic biaxial bending device.

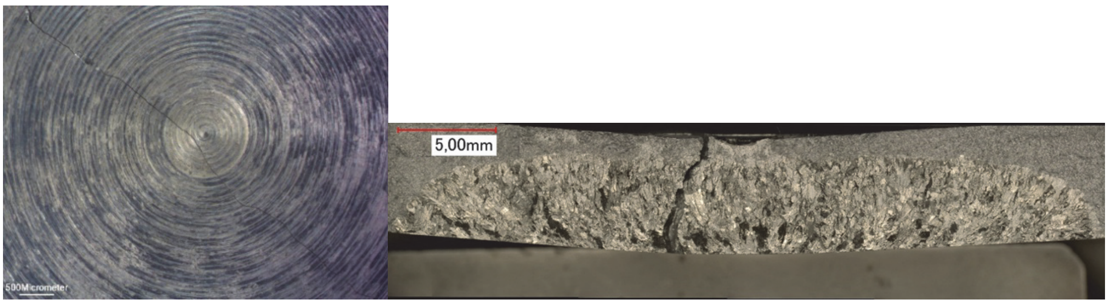

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Figure 5: Macroscopic fatigue crack after testing a disc specimen under biaxial bending, a) lower face of the specimen and b) after breaking it under monotonic quasi-static loading.

CONCLUSION AND PROSPECTS

A new ultrasonic fatigue testing device generating a biaxial proportional stress state with a positive loading ratio has been presented. VHCF tests were performed on a cast aluminum alloy already tested in the literature in HCF regime under a similar stress state. The new results are consistent with data from the literature. Self-heating is moderate, but the stop criterion could be improved to detect smaller crack. Crack initiation will be investigated, as two competing parameters play a role: the biaxial stress state which is maximal on the surface, and the possible presence of subsurface defects in a cast material.

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