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Device for carrying out environmental very high cycle fatigue tests with ultrasonic excitation in asymmetric push–pull mode

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ABSTRACT

The increasing lifetime of many engineering components leads to a growing demand for accelerated testing methods. Fatigue failure of components submitted to cyclic loading at stress levels below the endurance limit occurs even beyond 10^7 cycles which has been the traditional limit for fatigue testing in most laboratories. Test programs covering this range of cycles on servo-hydraulic or resonance machines are very time consuming. Therefore methods for very high cycle fatigue (VHCF) testing at ultrasonic frequencies have been developed and are now used routinely. These methods rely on the formation of a longitudinal standing ultrasonic wave inside a test specimen. The wave exerts an alternating tensile and compressive stress on the specimen. Because of their origin in a standing wave, the tensile and compressive stresses usually have the same magnitude, i.e. the test is carried out under fully reversed conditions. Several test rigs have been proposed and built to overcome this drawback by coupling an ultrasonic loading device with a classical uniaxial test bench and superposing the ultrasonic stress to a constant or slowly varying stress. We present a different approach for overcoming that limitation where the constant stress is generated by a pressure difference. This approach is especially useful for testing in hazardous environments since all movable parts like pull rods passing through the walls of the test chamber are avoided.

We describe the design and the performance of such a VHCF device and present first test results demonstrating the deterioration of the lifetime of Inconel 718 specimens in high pressure gaseous hydrogen compared to argon.

1. Introduction

Many engineering components are subjected to cyclic loading which may lead to fatigue failure after large numbers of cycles. Depending on the stress amplitudes, different fatigue regimes requiring different testing techniques can be distinguished. In the low cycle fatigue (LCF) regime with high stress levels the tested specimen deforms plastically on a macroscopic scale; failure typically occurs after less than 10^5 cycles. Such tests are usually carried out in strain control by means of servo-hydraulic test benches.

When stress levels are decreased, plastic deformation happens on a microscopic scale and is limited to some of the grains [1]. This regime is called high cycle fatigue (HCF). Testing is often carried out using resonance machines which operate at higher frequencies (typically up to 300 Hz) than servo-hydraulic machines and lower power consumption.

The upper limit of the HCF regime is generally put at 10^7 cycles, a criterion that is related to the fatigue limit for LCF [1,2]. Testing in the very high cycle fatigue (VHCF) [3–5] or ultra-high-cycle fatigue (UHCF) [6] regime i.e. beyond 10^7 cycles is conveniently carried out by means of ultrasonic excitation around 20 kHz. In the VHCF regime, plastic deformation occurs only in a very limited number of grains [1]. Crack initiation tends to shift from the surface (LCF, HCF) to the bulk of the material. Tests carried out in this regime can lead to failure through fatigue at stress levels below the traditional fatigue limit, thus putting the concept of a fatigue limit into question [7,2,4].

As stresses in ultrasonic devices originate from standing waves VHCF investigations are normally limited to symmetric push–pull modes ($R = -1$), cf. Eq. (4). Several designs have been proposed to overcome this limitation by combining an ultrasonic test device with a classical universal test bench allowing the superposition of static (i.e. constant or slowly varying) and ultrasonic stresses [8–10]. Some devices also allow studying fatigue under particular conditions like corrosive environments, cryogenic temperatures, or vacuum [11–13]. Using such devices for tests in controlled environments requires putting the test specimen in an autoclave and connecting it to pull rods passing through the walls of the autoclave.

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We present a design based on a different principle which also allows to superpose a high frequency and a static stress. The static stress is generated by means of a pressure difference maintained in two separate chambers inside an autoclave. This design does not require a classical test bench and it eliminates pull rods passing through the walls of the autoclave. This is particularly advantageous when tests are to be carried out in hazardous environments like explosive or toxic gases at high pressure because movable rods passing through the walls of the autoclave would increase the risk of leakage.

2. Experimental setup

In this section, the novel experimental setup for ultrasonic VHCF testing is described. It has been developed to provide a means for testing materials in gaseous hydrogen at high pressure. A general description of VHCF testing by ultrasonic excitation can be found in the literature [14].

2.1. Ultrasonic excitation

If a longitudinal ultrasonic wave is coupled into a cylindrical rod and it meets the resonance condition:

$$\frac{\lambda}{2} = x_0 \tag{1}$$

where λ is the wavelength and x_0 the length of the rod, a standing wave will result. From the displacement u, the axial elastic strain ϵ and the stress σ can be determined:

$$\epsilon = \frac{\partial u}{\partial x} \tag{2}$$

$$\sigma = E\frac{\partial u}{\partial x} \tag{3}$$

where E is the Young's modulus of the material.

The ultrasonic wave is created by means of a piezoelectric transducer. For transferring the oscillations to the specimen the latter is mechanically fixed to the piezoelectric transducer. In order to increase the amplitude of the oscillations, in most cases an acoustic horn (booster) is installed between the piezoelectric transducer and the specimen. The use of a longitudinal sound wave leads to a displacement along the axis of the rod and to a uniaxial stress along the axis of symmetry. The amplitude of the standing wave is controlled by the amplitude of the mechanical oscillations transferred from the piezoelectric transducer to the specimen. Consequently, the standing wave has a maximum of displacement at that end of the specimen where the specimen is excited.

From the resonance condition (Eq. (1)) follows that a second maximum of displacement is situated at the other end of the specimen and a node in between. The oscillation of the displacement at both ends of the specimen occurs with the same amplitude and frequency but a phase difference of π: the specimen undergoes a symmetric stretching vibration.

From Eqs. (2) and (3) follows that the strain and stress distributions have nodes at the ends of the specimen (where displacements are at their maxima) and maxima at the center (at the node of displacement).

The stresses originating from a standing wave are symmetric with a mean value of zero. Consequently, the stress ratio is:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = -1 \tag{4}$$

2.2. Concept of the test bench

The test bench we present here has been developed for carrying out VHCF tests at high pressure hydrogen atmospheres (up to 35 MPa) at stress ratios $R > -1$. The basic idea is to use the static or slowly varying gas pressure to apply a tensile stress on the specimen which is superimposed on the oscillating stress resulting from the ultrasonic excitation. This approach has the advantage that no further test bench is required for adding the static load and in particular there is no need for moving mechanical parts (such as pull rods) to pass through walls of the pressure chamber. Especially for tests in hazardous environments that approach increases the safety of the experiment since the joints between the pull rods and pressure chamber would present a considerable risk for leakage.

Fig. 1 shows the basic layout of the autoclave and load train. The load train is composed of a piezoelectric transducer on the bottom of which the top acoustic horn is attached followed by the specimen and the bottom horn.

The top horn has two functions: through the reduction of diameter from the top to the bottom, it increases the excitation amplitude transmitted from the piezoelectric transducer to the specimen, while it closes the pressure chamber at the top.

The specimen is attached to the top horn. The hourglass shape amplifies the stress at the center of the specimen and ensures that failure occurs at that position. This is important since the relationship between the local stress level at the specimen center and the excitation voltage of the piezoelectric transducer will be established by means of a calibration procedure (see Section 2.5).

At the end of the load train, the bottom horn is attached to the specimen. The function of the bottom horn is to divide the pressure vessel into two separate chambers. The horn is only fixed to the specimen and does not directly touch the walls of the pressure chamber. The thicker part of the bottom horn has a circular groove in which a gasket is placed (see Fig. 1). The gasket separates the upper from the lower pressure chamber. If the pressures in both chambers are different an axial force will be applied to the bottom horn. When A_{AC} is the cross section of the autoclave at the height of the gasket and Δp the pressure difference between the pressure chambers, this force is simply:

$$F = A_{AC}\Delta p \tag{5}$$

Since the bottom horn transmits the same force to the specimen, a static stress σ_{SP} results which depends on the cross section A_{SP} of the specimen at its waist:

$$\sigma_{SP} = \frac{F}{A_{SP}} \tag{6}$$

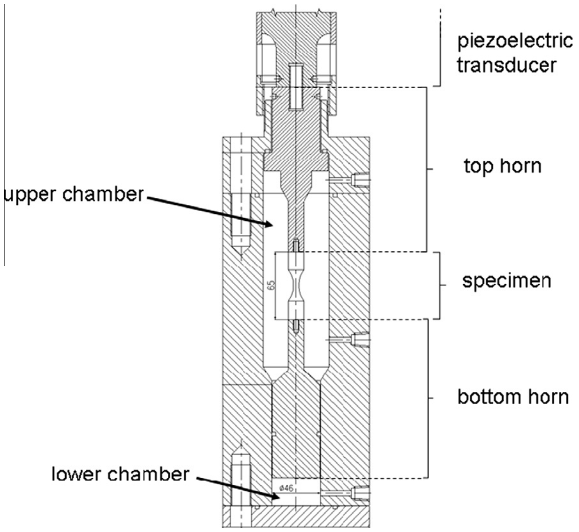

Fig. 1. Schematic of the autoclave and load train.