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Combined cycle fatigue of 7075 aluminum alloy – Fracture surface characterization and short crack propagation

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ABSTRACT

Aim of this study is an interpretation of the influence of variable-amplitude (VA) cycles superimposed to low-frequency loads on fatigue life of 7075-T651 Al-alloys. Constant-amplitude (CA) 20 kHz stress/strain-life (*S–N*) and (ε–*N*)-curves with and without superimposed mean loads serve as basis. For combined fatigue loading, life-time measurements were performed. Life-time estimations based on the *S–N* results reveal a damaging effect of the superimposed ultrasonic vibrations in the high cycle fatigue (HCF) and the very high cycle fatigue (VHCF) regimes. The CA and VA-life time results are correlated with fractographic observations. An interpretation of fatigue lives under combined low and high-frequency VA-loading is proposed considering small/short-crack propagation and arrest mechanisms.

1. Introduction

The loading histories for many rotorcraft and fixed-wing aircraft components contain a large percentage of low amplitude cycles. The spectrum characteristic is usually such that, small-amplitude cycles are superimposed on top of steady, maneuver, carrier or duty cycles. Usually, these small-amplitude cycles arise from several discrete sources such as environment and structural vibrations. Examples of these loadings are very common: buffet, gust and flutter loadings on fixed-wing aircraft and vibratory loadings resulting from primary and secondary modes on rotorcraft. These loads are also typical on aircraft engine components. The small amplitude loading cycles alone fall under the traditional definition of high-cycle fatigue (HCF, life > 10^5 cycles), while the main cycles usually fall under the low-cycle fatigue (LCF, life < 10^5 cycles) categories. Moreover, the small-amplitude cycles usually occur at higher frequency than the main-cycle loadings [1–7].

Although these combined cyclic-fatigue (CCF) loadings, i.e., combination of VHCF loadings superposed on slowly varying LCF loadings, are commonly encountered, no reliable methods yet exist to predict damage and failure modes/mechanisms for these types of service histories. The standard practice is to either ignore the damage contribution from small cycles or assign a predefined damage without any qualifying data.

To characterize fatigue crack initiation and crack growth lives from service spectrum loadings of this nature, critical fatigues tests are being performed at University of Natural Resources and Life Sciences, Vienna, BOKU. The goal of these tests was to evaluate the influence of combined effects of mean stress and superimposed small cycles on fatigue life. This paper discusses experimental work and results from one set of critical tests that have been carried out. These tests focused on perturbing the slowly varying carrier/duty cycle with smaller high frequency cycles which are sinusoidal or random in nature. The carrier/duty cycles are of constant and variable amplitude, of different wave profiles and at different frequencies [7].

The paper is organized as follows: following this introduction, a description of the experimental set-up and loading process are given in Section 2. Details of both CA and VA test results are presented in Section 3. Discussion and analysis of the CA and VA results are provided in Section 4 followed by concluding remarks and a short outlook in Section 5.

2. Experimental details

2.1. Tests overview

Fatigue tests were performed at University of Natural Resources and Life Sciences, Vienna, BOKU with testing equipment consisting of an ultrasonic-fatigue device and a servo-hydraulic machine [8,9]. Experimental life-time results were analyzed and correlated

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with fractographic studies. The resulting fracture surfaces were evaluated with an optical and electron scanning microscope (SEM) in the secondary emission (SE) and back scatter (BS) mode and by energy dispersive X-ray analysis (EDX). Specimens that did not fail until at least 10^9 cycles were reloaded with a higher load until failure in an attempt to identify reasons for non-failure in the expected range. Measurements under various VA tests containing either sinusoidal or rectangular carrier waves at low frequencies (0.1–20 Hz) with superimposed high-frequency 20 kHz-ultrasonic vibrations of CA or VA blocks have been reported earlier [7,10–13] and therefore are not discussed in this study.

2.2. Material

The material studied is AA 7075-T651 plate material. Chemical composition and mechanical properties are listed in Table 1. The heat treatment of the 20 mm thick AA 7075 plates was T651 (certified). The resulting microstructure accordingly shows elongated grains with an extension of 15–23 μm in the short transverse and long transverse direction and 2–8 mm in the longitudinal direction. The elastic modulus E was determined dynamically and for comparison also statically. The dynamic measurement was performed by measuring the resonance frequency of a cylindrical rod of the same material batch vibrating at the ultrasonic resonance frequency of 19.3–19.4 kHz. The static values were obtained with two kinds of experiment, one in tension–compression and one during bending loading (for details see [14]). The three procedures led to similar values, therefore, a modulus of elasticity of 72.0 GPa was used for all subsequent evaluations. Fatigue test specimens were machined from plates of 20 mm thickness. Specimens were of hour-glass type (total length without screws 54.8 mm, outer diameter 14 mm) with a central cylindrical part (length 10 mm, diameter 4 mm) (Fig. 1) and were finished by polishing with abrasive paper up to grade #600 parallel to the longitudinal axis (rolling direction). Besides specimen shape and dimensions, the longitudinal stress profile is shown for both low-frequency and high frequency loading in Fig. 1.

2.3. Experimental setup

Low-frequency loading is performed with a servo-hydraulic machine in force control mode. Square wave shapes at different frequencies (0.4 Hz, 0.5 Hz, 1 Hz or 2 Hz) are generated at zero or tensile mean loads (R = 0.05–0.06 (named 0 in the following), or +0.5).

20 kHz amplitudes are superimposed using ultrasonic-fatigue equipment working in resonance [8,9]. In order to obtain resonance all mechanical parts including the specimen have to be dimensioned such that, standing longitudinal waves are generated. In this case, the maxima of vibration are located at the ends of the specimen and the maxima of strain and stress arise in its center. With an inductive sensor [8] (developed by W. Kromp and S. Stanzl), the vibration amplitudes, measured at one specimen end, allow calculating the cyclic elastic strain amplitudes in the central cylindrical part of the specimens after careful microscopic calibration. The results are cross-checked with strain-gauges, assuming linear-proportional behavior of strain- and vibration

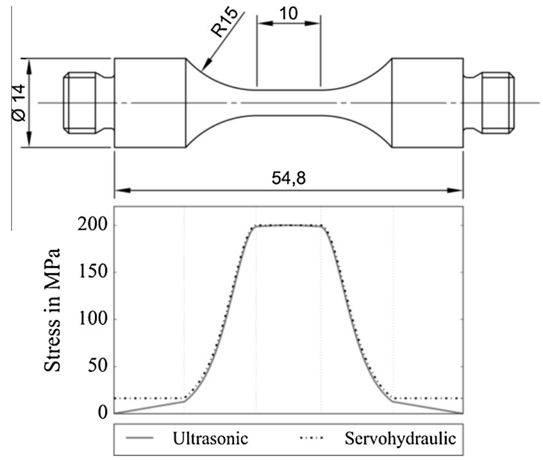

Fig. 1. Specimen shape and dimensions (in mm) and longitudinal stress profile for servo-hydraulic and super-imposed ultrasonic loading.

amplitudes. The signals of the vibration measurements are stored and evaluated electronically on-line. In addition, they serve as feed-back control for a closed-loop control of the ultrasonic fatigue signals. The accuracy of equipment is high: the amplitude accuracy is 2% and that of the frequency ±1 Hz [9]. Assuming linear elastic response of the material, the cyclic stress amplitudes are calculated by multiplying the cyclic strain amplitudes with the elastic modulus, which is determined by another calibration procedure prior to the experiments (see Section 2.2).

With this test set-up, both continuous operation and intermittent loading with periodic pauses comprising of several hundred up to several thousand cycles [8] are possible. The pulse-pause operation is needed for cooling purposes on one hand and also for performing VA loading as described in Section 2.4. In order to avoid heating of a specimen owing to high-frequency damping, the specimen is cooled with forced air besides periodic-pulse/pause operation. VA loading may range from two-step to quasi-random tests. It has to be considered, however, that realizing single randomly changing cycles is not possible owing to the resonance type of wave generation. Therefore the variation of single cycles is replaced by constant amplitude pulses [8] consisting of 500 cycles as illustrated in Fig. 2a (An irregularity of 1 means a ratio of 1 of the expected rate of mean crossings to the expected rate of peaks). In the present experiments, one block (pulse) consists of typically 2000 or 4000 or 5000 cycles. Though shorter blocks (or ultimately single cycles) at every load level are desirable, only block loading is feasible as the ultrasonic resonance equipment needs a few milliseconds to reach the nominal vibration amplitude, especially with a rapidly varying pre-load, rendering the choice of shorter blocks pointless.

The ultrasonic device is combined with the servo-hydraulic testing machine in order to allow mean stresses larger or smaller than zero and to allow different carrier loads. The ultrasonic-vibration amplitudes are converted to high-frequency 20 kHz-signals and superimposed to the – low frequency signals (2 Hz, 1 Hz, 0.5 Hz or 0.4 Hz).

Table 1
Chemical composition (in wt.%) and mechanical properties of 7075 T651.

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Ga	V	Al
0.11	0.16	1.5	0.083	2.6	0.18	0.005	5.73	0.033	0.013	0.015	REM

Modulus of elasticity E (GPa)	Tensile strength (MPa)	Yield strength (MPa)	Elongation A (%)	Hardness HV
72.0	589	524	12	163