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Very high cycle fatigue measuring techniques

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A B S T R A C T

Ever since high-strength steels were found to fail *below* the traditional fatigue limit when loaded with more than 10^8 cycles, the investigation of metals' and alloys' very high cycle fatigue properties has received increased attention. A lot of research was invested in developing methods and machinery to reduce testing times. This overview outlines the principles and testing procedures of very high cycle fatigue tests and reports findings in the areas of crack formation, non-propagating small cracks, long crack propagation and thresholds. Furthermore, superimposed and variable amplitude loading as well as frequency effects are reported.

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1. Introduction

Many constructions and parts of moving machines (e.g. car wheels, axles, motors, aircraft and space equipment) are subjected to very high numbers of cycles. Trains, off-shore structures, and bridges, for example, have to withstand more than 10^{10} cycles. Unfortunately, some material properties, such as the fatigue limit or the cyclic stress intensity threshold, cannot be extrapolated from measurements at lower numbers of cycles. One single measurement in the range of 10^{10} cycles with, e.g. a conventional 20 Hz servohydraulic machine would however take 17 years. Using a 20 kHz ultrasound fatigue device shortens this testing time to less than a week. Consequently, the interest in new techniques for tests in the very high cycle fatigue (VHCF) regime is on the rise.

Existing standardised procedures provide important input on measuring techniques and the correct application of measurement devices (standards of ASTM, ISO etc.) for standard equipment. Nevertheless, the development of new testing facilities and methods requires input from new scientific insights. The importance to develop VHCF testing has two main reasons: First, it could be shown 25 years ago that some materials, such as high strength steels, failed at stress levels which were considered as "safe" (i.e. below the traditional fatigue limit in the VHCF regime) until then. Secondly, there are still no satisfying models for life time predictions under fatigue loading with complex stress–strain conditions, e.g. with variable amplitudes containing high numbers of very low amplitudes. This study will briefly mention the results of research on the reasons and conditions for failure in the VHCF regime. First of all, however, a short survey of testing machines, measuring and evaluation procedures will be given.

2. Testing machines

2.1. Servo-hydraulic testing machines: 1000 Hz versus conventional machines

For tests up to 10^7 cycles, one commonly uses conventional servo-hydraulic machines. These machines typically work at frequencies from around 20 Hz for most technical materials up to about 50 Hz. For the measurements, a specimen is loaded with a hydraulic cylinder which is driven by a servovalve-feedback control. Such a procedure generates the oil pressure anew for each of the cycles; thus, the overall energy consumption is significant, and the large part of the power consumption which is transformed to heat must be dissipated by appropriate cooling.

From 1997 onwards, servo-hydraulic machines operating with frequencies of 1000 Hz were developed for purposes requiring higher number of cycles in a certain time [1]. These newer machines use a high-flow voice coil servovalve, designed to allow a higher response speed and flow rate. Since the voice coils are based on the electrodynamic principle of an audio speaker to regulate the pressure changes of the hydraulic fluid, only the coil springs in the pilot stage are mechanically stressed. Thus, the machines can achieve large deflections at 1000 Hz, avoiding premature failure of the valve, to perform high-frequency, high-performance testing. To minimize possible resonances and make the load frame less flexible and bulky, these machines are equipped with an enforced cross head and shorter, broader columns as compared to the customary 250 kN load frame. Therefore, displacements of up to

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±0.1 mm and dynamic loads of ±20 kN can be guaranteed. The problem of acceleration effects owing to the moving mass of the load train is met by the application of accelerometers, whereby the effects can be counteracted in the control loop with the appropriate testing procedures.

Zimmermann and Christ [2] reported on the power response and the control accuracy characteristics of these high-frequency testing machines. Their measurements showed that, for constant amplitude tests with steps of 100 Hz on an aluminium alloy and a duplex-steel, the best control behavior was reached at 760 Hz. In this range, the deviation was found to be less than 3% of the nominal amplitude value. However, the load response for tests with load blocks containing 2500 cycles with rapidly changing amplitudes was too low.

2.2. Resonant and forced-vibration machines (shakers)

For more than 100 years, resonant testing machines have been built; a short historical overview thereof is given by George et al. [3]. Compared to the hydraulic testing machines mentioned in the last section, resonant fatigue testing machines allow higher testing frequencies and have a lower power consumption. Traditional resonant testing machines are realized as mechanical vibration systems: a spring-mass functions as electromagnetically driven oscillator, vibrating at its eigenfrequency. The test specimen, with its elastic properties, is part of the vibration system. Characteristically, the frequencies of such systems lie in the range of 50–250 Hz. The power consumption is about 0.5 kW, which amounts to only a few percent of a servo-hydraulic system's energy use. For more than 50 years, electromagnetically driven resonance testing machines operating with 250 kN and 100 kN (e.g. Fractonic 7801, Rumul, CH) have been built to conduct high cycle fatigue tests on stiff specimens (cf. [4]).

Nowadays, a variety of forced vibration-based systems is available [3,5–8]. Two test machines operating in the frequency range of 500 Hz or 1.8 kHz were suggested in 2002 [5]: the first uses a pneumatic cylinder fitted in a rigid test frame to produce a mean load, and an electrodynamic shaker to apply the oscillatory loads. The second machine makes use of a magnetostrictive high frequency actuator and a large mass which is stiff for high frequency loads but compliant for a low frequencies or static mean loads. Both techniques were showed to be suitable for fatigue testing, as was demonstrated by measuring the *S–N* and the fatigue crack growth threshold values of Ti-6Al-4V. A further timesaving method using driven oscillations was reported in 2004 [3], where an appropriately designed plate specimen is base-excited and driven into a high frequency resonance mode. The system allows for fully reversed uniaxial and biaxial bending stresses, and its applicability was proved by measuring plate specimens made of steel, Ti-6Al-4V and 6061-T6 aluminum. Morrisey and Nicholas [6] compared the experimental results of the electromagnetic shaker systems, an ultrasonic fatigue system (discussed below) and conventional servo-hydraulic test systems on Ti-6Al-4V specimens: No frequency effects on the endurance limit became evident.

The Fraunhofer–Institute for Structural Durability and System Reliability LBF develops machines capable of applying variable and user defined signal forms [7]. This can be achieved by combining two kinds of driving systems: a low-frequency actuator on the one hand (e.g. a hydraulic system for static loading or loading at frequencies around the specimen's eigenfrequency) and a high frequency actuator (e.g. a piezo-electrical system) on the other hand. At 1 kHz, forces of 600 N should allow measuring elastomere parts. A second machine using a piezo-electric driver uses a one stack actuator [8]. This system offers the possibility of applying testing frequencies of up to 1000 Hz and forces up to 10 kN, and can be applied in constant amplitude as well as variable amplitude testing.

2.3. Rotating bending loading

Rotating bending machines were the first fatigue loading machines and Wöhler was the first to use them for measuring fatigue data and endurance limits [9]. Therefore, the *S–N* curves were later named after him. These machines received increased importance again about 25 years ago, when Japanese scientists, measuring *S–N*-curves of high-strength steels, discovered the formation of interior crack initiation at very high numbers of cycles, typically above 10^8 cycles and the formation of so-called 'fish eye' fractures [10–13] at very high numbers of cycles, which can be reached in reasonable testing times using this technique. Rotating bending machines have several important advantages. They are robust and reliable, which explains their frequent application in long-term testing procedures, and their construction and operation is cheaper than that of servo-controlled equipment. The frequency range they achieve reaches from about 0.1 Hz to 200 Hz. Rotating bending equipment is available in a large variety of technical realizations; a thorough description would go beyond the scope of this paper, but a fundamental overview is given in [14]. The principle of rotating bending machines is simple: a predefined bending stress is applied to a cylindrical specimen via a certain bending moment. The simplicity of the setup makes it ideal for fatigue-strength testing. Usually, the specimen is rotated around the bending stress axis. This has the disadvantage that the stress in the cross-section of the specimen changes (in tension–compression tests, contrariwise, the stress is relatively uniform across an unnotched specimen's area). The stress change can be formulated in the elasticity relationship $\sigma = Mc/I$, where M is the bending moment applied to the specimen, c is the distance from the specimen surface to the neutral axis, and I is the cross-sectional moment of inertia.

The variability of the stress is, however, not the only fact one has to be aware of: the stresses that are measured at the surfaces are lower than expected. This is due to non-elastic yielding [14,15]. Due to the applied bending moment, a plastic deformation can be induced in the outer regions of the specimen [15]. Unloading then results in an elastic spring-back, a residual stress remaining in the material. Consequently, the stresses in the *S–N*-curve induced through rotating bending are higher than those for axial loading (i.e. the life-time seems to be significantly higher). Being aware of this fact is important in explaining the so-called duplex *S–N*-curves obtained in very high cycle tests of HSLA steels (SUJ2) [10–13]. Murakami et al. [10], for example, noted that rotating bending of specimens with 3 mm diameter and approximately 2 mm of stressed length resulted in a duplex curve, whereas tension–compression tests of specimens with 7 mm diameter and 20 mm of stressed length did not give duplex curves. In addition, increasing the number of experiments resulted in a less pronounced duplex shape of the rotating bending tests, which was due to the smaller mean value of the stress gradient in all tested specimens. In consequence, the duplex shape of the *S–N*-curves is not regarded to be very relevant for larger machine parts [10].

The difference between the rotating bending and the tension–compression technique has not only been investigated for fatigue life and crack formation, but also for crack propagation [16,17]. What makes such investigations extremely difficult is the fact that in rotating bending specimens, the crack propagates into the specimen and is thus not observable by means of optical detection. Furthermore, contacting rotating specimens is very difficult, making conventional means of electric detection impracticable. Thus, the setup has been changed [16], clamping a non-moving specimen at one end and loading its other end with a rotating force. In this setup, crack lengths can easily be measured by means of the direct current (DC) potential drop technique. A similar reverse bending rig was developed by [18] and used to investigate the short crack

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