Available online at www.sciencedirect.com
SCIENCE DIRECT
International Journal of Fatigue 27 (2005) 129–141
International Journal of Fatigue
www.elsevier.com/locate/ijfatigue

Influence of cyclic loads below endurance limit or threshold stress intensity on fatigue damage in cast aluminium alloy 319-T7

H. Mayer [a,*], C. Ede [a], J.E. Allison [b]

[a] Institute of Physics and Materials Science, BOKU, Peter-Jordan-Str. 82, A-1190 Vienna, Austria
[b] Materials Science Department, Ford Research Laboratories, Dearborn MI 48124-2053, USA

Received 21 January 2004; received in revised form 12 May 2004; accepted 9 June 2004

Abstract

The aluminium alloy 319-T7 shows an endurance limit at approximately 10^7 cycles and has been used to study the influence of numerous stress amplitudes below the endurance limit on fatigue damage. Variable amplitude tests have been performed with short repeat two-step sequences of stresses above and below the endurance limit. If high stresses of the variable amplitude sequence are 40% or more above the endurance limit, cyclic loads below the endurance limit reduce lifetimes, and the detrimental effect is more pronounced the larger the low stress amplitudes. Lifetimes could be reasonably well predicted with Miner calculations and extrapolating the S–N curve with reduced slope below the endurance limit. Beneficial influences of numerous low load cycles were found in some specimens, when the maximum stress of the variable amplitude sequence was only slightly (15%) above the nominal endurance limit. Accelerated crack growth was found in fracture mechanics variable amplitude tests and repeat sequences with high stress intensity of 25% or more above the threshold stress intensity and large numbers of cycles below. Numerous cycles below threshold stress intensity, however, may cause an arrest in fatigue crack growth, if the high stress intensity of the variable amplitude sequence is only slightly (15%) higher than the constant amplitude threshold.

Keywords: Endurance limit; Fatigue limit; Threshold stress intensity; Variable amplitude loading; Damage accumulation; Ultrasonic fatigue

1. Introduction

Constant amplitude fatigue tests are frequently used to characterize the fatigue properties of materials. Such experiments are typically performed in the regime below approximately 10^7–10^8 cycles, since investigations at larger numbers of cycles would require excessive testing times using conventional fatigue testing techniques, i.e. servo-hydraulic or rotating bending. However, number of cycles imposed on components in several applications in transportation industry, including engine parts or load-bearing components in vehicles or railway structures, for example, can be far greater, e.g. 10^9 cycles or more. Moreover, such components are typically stressed at varying rather than constant load amplitudes where the load spectrum includes large numbers of relatively small loads.

Fatigue damage of small load cycles in materials, which do not show an endurance limit, including most aluminium wrought alloys and several aluminium cast alloys [1], can be estimated from the S–N curve, which is extrapolated into the very high cycle regime and using one of the numerous damage accumulation consideration [2]. The oldest and best-known method is the so-called Miner rule [3,4], which assumes linear fatigue damage accumulation and is based solely on the S–N curve. Damage caused by one cycle at stress amplitude σ is $1/N(\sigma)$, where $N(\sigma)$ is the number of cycles to failure in constant amplitude tests. Failure at varying amplitudes is expected when the damage is accumulated to a critical value, which was originally chosen equal to unity [4]. The so-called "relative Miner rule" [5] considers constant damage sums under comparable loading conditions, which however are not necessarily equal to unity (e.g. 0.3 [6]).

In materials, which show an endurance limit, like the cast aluminium alloy 319-T7 investigated here [7], the

* Corresponding author. Tel.: +43-1-47654-5161-10; fax: +43-1-47654-5159.
E-mail address: herwig.mayer@boku.ac.at (H. Mayer).

0142-1123/$ - see front matter
doi:10.1016/j.ijfatigue.2004.06.004

Miner rule considers cyclic loads below the endurance limit as non-damaging. Such low load cycles, however, may cause fatigue damage, although the stresses are not sufficiently high to propagate a crack to fracture. For example, fatigue cracks initiated in the ferrite of carbon steel at stresses below the endurance limit and their growth was arrested when the crack encountered microstructural barriers such as pearlite [8,9]. Small fatigue cracks have also been observed in Ti-6Al-4V at cyclic stress amplitudes below the conventional endurance limit [10]. In presence of small stress raisers, fatigue cracks initiated in carbon steel and 70/30 brass at stresses well below minimum amplitude necessary to fracture the specimen and caused initial damage for further cycling at higher stresses [11]. The material used in the present investigation (319-T7) shows fatigue cracks initiating at casting porosity at stresses below the endurance limit, and considerably higher stresses are necessary to propagate them to final fracture [7].

In the high and very high cycle fatigue regime, in-service loading typically includes large numbers of cycles at low load amplitudes. Some cast aluminium components, for example, are designed to survive 5×10^8 cycles in service. When the aluminium cast alloy A356-T6 was tested using close-to-real random sequence and omission level of 25% (i.e. the minimum stress amplitude actually included in the random experiment was 25% of the maximum stress of the load sequence), only 1% of the stress amplitudes were higher than the endurance limit at 10^9 cycles [12]. If cyclic stresses below the endurance limit cause fatigue damage, this would be especially important in the very high cycle fatigue regime. For component testing using variable amplitude loading, for practical reasons low load cycles are sometimes omitted from the load sequence to accelerate the testing. This leads to the question where the omission load level should be chosen, since high omission levels significantly reduce testing times, however, eliminate possible damage of numerous lower load cycles. Omission levels with respect to the endurance limit [13] or the maximum stress of the sequence and the strain hardening behaviour of the material [14] have been proposed. Some studies clearly indicate contributions of small load cycles to fatigue damage in variable amplitude testing. Cycles to failures are lower [13,15,16] and fatigue crack propagation rates are higher [17] when low omission levels are chosen. In other studies, cycles to failure could be predicted reasonably well ignoring possible damage below the minimum stress amplitude required for failure in constant amplitude tests [12,18].

One method to include possible damage of amplitudes below the endurance limit in damage accumulation calculations is the extrapolation of the S–N curve to lower cyclic stresses [19–21]. Experimental verification of contributions of cycles below the endurance limit to fatigue damage is however difficult. Linear damage calculations may be insufficient due to several reasons other than damage of low load cycles. Most prominent are sequence effects, which make sequences of high load amplitudes first and low amplitudes afterwards more damaging compared to the reverse ordering [22–27]. Inaccurate predictions may also be caused by mean stress fluctuations, residual stresses and overload effects, for example [6,28,29]. Another experimental problem verifying influences of load cycles below the endurance limit is the scatter of fatigue data, which makes it necessary to test large numbers of specimens. Additionally, the endurance limit must be determined at high numbers of cycles to guarantee, that specimens would not have failed, in particular in the very high cycle regime, in constant amplitude loading at the low amplitude [30].

In this investigation, the influence of load cycles below the endurance limit and threshold stress intensity is studied in variable amplitude tests using relatively short high–low repeat sequences to diminish sequence effects. Specimens have been loaded with minimum 10^9 cycles to determine the constant amplitude endurance limit, and two-step variable amplitude tests have been performed to minimum 5×10^9 cycles if specimens did not fail. For the two-step variable amplitude tests, a total of 7.5×10^{10} load cycles were applied. Forty-one specimens have been loaded with more than 10^8 cycles to assess statistical variation. In fatigue crack growth tests, arrest of fatigue crack growth under variable amplitude loading was assumed when no detectable crack growth was observed within a minimum of 2×10^9 cycles.

These experiments obviously cannot be performed with conventional fatigue testing technique, since testing time would be too long. At testing frequency 50 Hz and using one testing frame, for example, the experiments would have needed about 50 years. Therefore, the ultrasonic fatigue testing method was used [31]. Previous investigations have shown that the influence of cycling frequency on fatigue damage at room temperature in 319-T7 aluminium is negligible, and comparable cycles to failure were found in servo-hydraulic tests at 40 Hz and in ultrasonic tests at 20 kHz [7]. The presented fatigue data determined at ultrasonic frequency are similarly applicable therefore for actual components stressed at far lower frequencies.

2. Material and experimental procedure

2.1. Material

Fatigue experiments were performed with the aluminium alloy 319. Chemical composition of the