APPLICATION OF ULTRASONIC FREQUENCIES IN FATIGUE

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Using ultrasonic frequencies offers a possibility to investigate the fatigue properties of materials in a very economic way. High cycle fatigue tests of the die-cast magnesium alloy AZ91 hp were performed. The endurance limit of this material is affected by the maximum size of cast voids and may be predicted on the basis of LEFM-principles. Near threshold constant amplitude and random amplitude fatigue crack growth measurements of metastable austenitic-ferritic steel are presented and interpreted on the basis of crack closure effects.

1. Introduction

Measurements of fatigue lives in the high cycle regime and crack growth rates in the threshold regime need long testing times with conventional fatigue testing equipment. Testing times and costs can be saved if the cycling frequency is increased up to 20 kHz. Ultrasonic equipment has achieved a high technical standard during the last years [1], so that, besides scientific investigations, reliable results for material research and application can be obtained. Two ultrasonic fatigue studies will be presented.

The use of lightweight metallic materials offers a great potential for weight reduction in the automobile industry. Recently, cast magnesium alloys have been developed for automotive applications [2]. Several car components, such as wheels or engine parts, have to survive up to one billion load cycles, and the high cycle fatigue properties of new construction materials are therefore of great interest. The processes of fatigue damage of f.c.c and h.d.p. alloys in inert environments and at low strain amplitudes are insensitive to the cycling frequency [3]. Therefore, the ultrasound method may be used for economic testing and development of aluminium and magnesium alloys.

Metallic materials frequently show a threshold stress intensity and a limiting crack growth rate of about 5×10^{-11} m/cycle under constant amplitude loading. No threshold, however, exists under random loading conditions [4] which makes investigations of very slowly growing cracks necessary. The ultrasound method is

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especially appropriate to study fatigue crack growth and crack closure mechanisms at very low cyclic loads, and the results of such a study performed with a metastable austenitic-bainitic steel will be presented [5].

2. Experimental procedure

In ultrasound fatigue experiments, specimens are excited to a push-pull resonance vibration at a frequency of about 20 kHz. The vibration amplitude or the vibration velocity of the specimen ends serves to control the magnitude of loading, and a frequency control guarantees that cyclic loading is in resonance. Details of ultrasonic equipment and control and evaluation procedures are described elsewhere [1]. In the present investigation fatigue experiments were performed at room temperature and at load ratio $R = -1$. Loading was applied in pulses consisting of 500 cycles each (pulse length approx. 25 ms). Periodic pauses (50–1000 ms) served to carry off the heat caused by internal friction. If necessary, a fan was used for cooling purposes. Increase of specimen temperature was typically 2–3 °C and was controlled with thermo-sensitive semiconductors attached to the specimen surface.

Lifetime investigations were performed with the high-pressure die-cast magnesium alloy AZ91 hp. Fig. 1a shows the dimensions of the specimens used for the constant amplitude fatigue experiments. The specimens surfaces were polished with abrasive paper of grade 1000 prior to the measurements. Fig. 1b shows the single edge notched specimen used for fatigue crack growth measurements of the metastable austenitic-bainitic steel GGG 100-B under constant and random amplitude loading. Crack growth data for constant stress intensity cycling are presented vs. the maximum cyclic stress intensity, K_{max}. In random amplitude fatigue crack growth tests, the mean fatigue crack growth rate during a load sequence is determined and correlated to the RMS (root mean square) of maximum cyclic stress intensities, K_{rms}. Details of ultrasonic random amplitude fatigue crack growth studies and GGG 100-B material are described elsewhere [5].

The maximum stress intensity, K_{max}, may be calculated from the vibration amplitude of specimen ends, u, or the velocity of specimen ends, v, the crack length, a, and the specimen width, W, according to a procedure described in [6]. In practice, however, it was found to be more reliable and accurate to calibrate ultrasonic fracture mechanic experiments using the strain amplitude in the specimen centre (the plane of the crack), which can be measured with strain gauges. Eventual small variations of the specimen thickness are taken into account by the strain measurement so that stress intensity calculations are less sensitive to slight variations of the specimen geometry. The strain amplitude, ε, for hypothetical crack length zero, which is directly proportional to the vibration amplitude or the vibration velocity, characterizes the magnitude of loading. Stress intensity may be calculated according to Eq. (1), where Y_u is the correction function for an amplitude controlled process and Y_v is the correction function, if the velocity of the specimen ends serves to

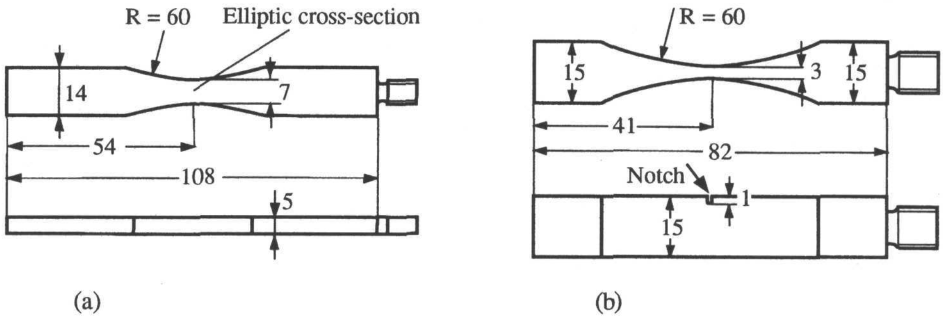


Fig. 1. Specimen shape used for lifetime (a) and fatigue crack growth (b) investigations.

control the ultrasonic fatigue crack growth experiment. The difference between Y_u and Y_v is caused by a decreasing resonance frequency with increasing crack length which affects the velocity of specimen ends at a certain vibration amplitude.

$$\begin{aligned} K &= \varepsilon \cdot E \cdot \sqrt{\pi a} \cdot Y_{u,v}\left(\frac{a}{W}\right), \\ Y_u &= 1.12 - 0.63\left(\frac{a}{W}\right) + 8.96\left(\frac{a}{W}\right)^2 - 28.4\left(\frac{a}{W}\right)^3 + 19.2\left(\frac{a}{W}\right)^4, \\ Y_v &= 1.12 - 0.04\left(\frac{a}{W}\right) + 0.53\left(\frac{a}{W}\right)^2 + 7.8\left(\frac{a}{W}\right)^3 - 24.0\left(\frac{a}{W}\right)^4. \end{aligned} \tag{1}$$

3. Results and discussion

3.1 Fatigue lifetime of high-pressure die-cast AZ91 hp

Lifetimes under constant amplitude fatigue loading of high-pressure die-cast AZ91 hp are shown in Fig. 2. Specimens which did not fail are marked with an arrow. Data points are approximated using an exponential function, and the lines indicate a 50% probability of fracture. Numbers of cycles to failure greater than about 10^7 are rare, and a well defined fatigue limit exists. No specimen failed within 10^9 cycles at a load level of 38 MPa.

The fatigue lifetimes of AZ91 hp are subjected to a pronounced statistical scatter which may be attributed to micro-structural defects. Voids are observed on the fracture surfaces of all broken AZ91 hp specimens. These defects act as starting points for the formation of fatigue cracks. Fig. 3 shows such a void as an example for this kind of casting defect on the fracture surface of an AZ91 hp specimen which was cycled with a load amplitude of 52 MPa and broke after 1.92×10^6 cycles. A correlation between cycles to failure and the areas of these material defects shows that the larger the voids at the crack initiation place are the earlier fracture occurs.

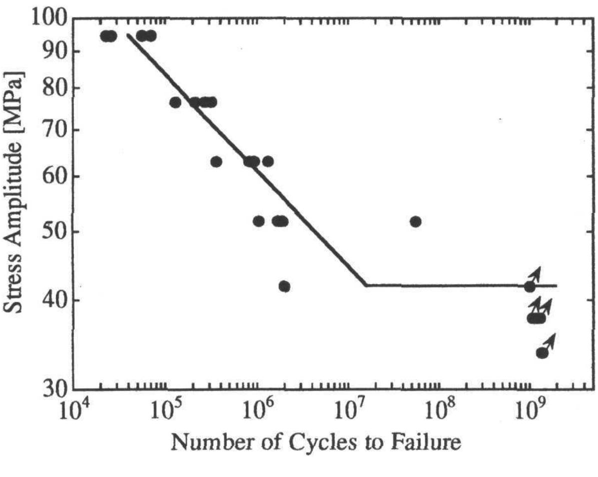


Fig. 2. Results of S-N fatigue tests with AZ91 hp.

Subdividing the fatigue process into fatigue crack initiation and crack growth until final failure, voids accelerate both damage periods. Voids cause stress concentration in nearby material and facilitate crack initiation. Stress amplitude, size, shape, and site of a void, as well as possibilities for slip in adjacent grains influence the number of cycles to form an initial crack. With increasing size of the casting defects the probability for early crack initiation also increases. Since a greater initially broken area (i.e. void + initial crack) causes a higher cyclic stress intensity amplitude of an initiated crack, the crack growth period at a certain cyclic load is shorter for larger flaws.

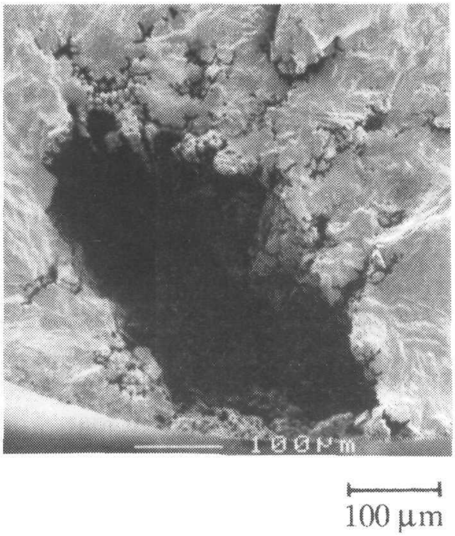


Fig. 3. Void in the fatigue crack initiation area of AZ91 hp specimen.

Based on fracture mechanical principles, it is possible to predict the fatigue limit of the investigated cast magnesium alloy: to propagate a short crack initiated from a void, it is necessary that cyclic stress intensity exceeds the effective threshold value. The largest voids of high-pressure die-cast AZ91 hp had approximate areas of 0.06–0.08 mm^2. Most fatigue cracks emerged from voids near the surface which indicates that surface flaws cause more severe material damage than inhomogeneities in the interior of a specimen. It may be assumed that the fatigue limit is reached if the stress intensity amplitude of an eventual short crack initiating from a flaw is below the effective threshold. For an arbitrary flaw at the surface of an (infinite) body, stress intensity may be calculated according to [7]

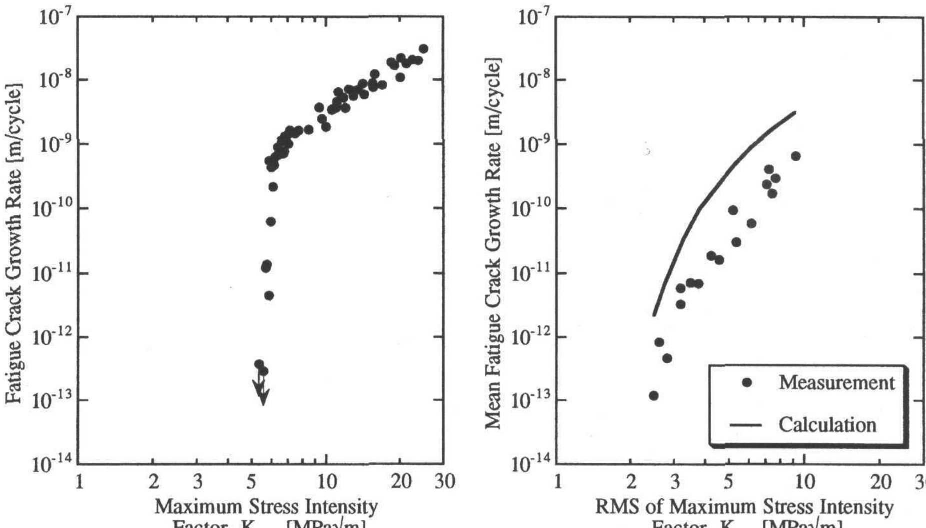
$$K_{I\max} = 0.65\sigma_{\max}\sqrt{\pi\sqrt{\text{area}}}, \quad \nu = 0.3. \tag{2}$$

The cyclic stress intensity factor is mainly a function of the initially broken area whereas the shape of the flaw influences the absolute value of K by less than 10% [7]. Unfortunately, no effective threshold of AZ91 hp for load ratio $R = -1$ is available. For $R = 0.05$ and $R = 0.5$, however, effective threshold values of $\leq$ 0.75 MPa $\sqrt{\text{m}}$ and 0.83 MPa $\sqrt{\text{m}}$, respectively, were measured [8]. If an effective threshold between 0.7 MPa $\sqrt{\text{m}}$ and 0.8 MPa $\sqrt{\text{m}}$ is estimated for $R = -1$ loading and if a maximum void area of 0.06–0.08 mm^2 is considered, the fatigue limit is calculated between 36 MPa and 44 MPa which is well in accordance with the experimental data. Additionally, it may be concluded that the fatigue limit of die-cast magnesium alloys significantly improve if the amount and maximum size of voids are reduced using proper casting techniques.

Crack growth rates of the initially formed cracks are low if cyclic stresses near the endurance limit are considered. The existing fatigue crack growth data for cast and wrought magnesium alloys [9] point to a minimum crack propagation rate of a growing crack of about 5×10^{-11} m/cycles at room temperature which is a typical lower limit for many metallic materials. Assuming minimum crack growth rates of about 5×10^{-11} m/cycle, crack advance to a crack length 0.5 mm will need maximum 10^7 cycles. For longer crack length, crack growth rates increase exponentially (Paris exponent of AZ91 hp is about 3.5 [8]). Therefore, it is plausible that near the endurance limit the crack extension period is mainly determined by the numbers of cycles to advance a short crack. When fatigue cracks emerged from relatively large voids, the crack initiation period for aluminium alloys was found to be negligible in comparison to the fatigue crack extension period [10], and a similar behaviour may be expected for present cast magnesium alloy. This leads to the conclusion that for cast magnesium alloys (as well as cast aluminium alloys) containing large voids, failure above 10^7 cycles is rare. One specimen, however, was found to fail after 5.5×10^7 cycles in the lifetime investigations (Fig. 2). For relatively small voids, the crack initiation period cannot be neglected and contributes significantly to the fatigue life [10], and lifetimes greater than 10^7 will be found. Nevertheless, most of the specimen contained relatively large voids, and they failed either at numbers of cycles below 10^7 or they survived more than 10^9 cycles. Considering only the fatigue crack growth period for the numbers of cycles to failure makes the pronounced fatigue limit observed for AZ91 hp plausible.

3.2 Fatigue crack growth properties of metastable GGG 100-B steel

The results of fatigue crack growth experiments at constant and random amplitude loading are shown in Fig. 4. A threshold for fatigue crack propagation is obtained at a maximum stress intensity factor of 5.7 MPa $\sqrt{\mathrm{m}}$ for constant amplitude cycling (Fig. 4a). Constant amplitude fatigue crack growth data and threshold value are similar for ultrasonic cycling of GGG 100-B and conventional fatigue testing [11]. No threshold could be found for random loading conditions, and fatigue crack growth rates down to 10^{-13} m/cycle were measured (Fig. 4b). The absence of a fatigue crack growth threshold is attributed to rare high cyclic stress intensities of the random sequence which exceed the constant amplitude threshold value, though the root mean square value of the whole sequence, K_{rms}, is smaller.



(a) (b)

Fig. 4. Fatigue crack growth rates of GGG 100-B for constant (a) and random amplitude loading (b).

Additionally, the line indicates calculated fatigue crack growth rates on the basis of a linear damage accumulation in Fig. 4b. Comparison of measurement and calculation shows that mean crack growth rates are overestimated by a factor of approximately 10. This pronounced crack growth retardation may be explained by crack closure and load interaction effects. The main contribution to crack closure in GGG 100-B originates from phase transformation in the stress field of the crack tip [5]. Rare high cyclic stress intensities of the random sequence give rise to strain induced phase transformation of a part of the austenitic phase into martensite in the plastic zone of the crack which leads to a net increase in the volume of the transformation region. As the enlarged material is left behind the advancing crack, the closure level is increased [12]. Crack growth following the high amplitude cycles in random loading experiments is, therefore, effectively retarded, and fatigue crack growth is remarkably lower during a random loading sequence than as predicted by linear calculations.

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