Endurance limit and threshold stress intensity of die cast magnesium and aluminium alloys at elevated temperatures

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Abstract

High cycle fatigue properties of the high-pressure die-cast magnesium alloys AZ91 hp, AS21 hp and AE42 hp and of the aluminium alloy AlSi9Cu3 are investigated at elevated temperatures. Fatigue tests are performed at ultrasonic cyclic frequency and load ratio \( R = -1 \). Compared with ambient air environment, the S–N curves determined in warm air of 125 °C (magnesium alloys) and 150 °C (aluminium alloy) are shifted towards lower cyclic stresses. The mean endurance limits at 10\(^9\) cycles of 41 MPa (AZ91 hp), 27 MPa (AS21 hp), 35 MPa (AE42 hp) and 61 MPa (AlSi9Cu3) are 70–90% of the respective stresses found in ambient air, and fracture mechanics tests delivered threshold stress intensities at elevated temperature of about 80% of the respective values at 20 °C. Fatigue cracks initiate, nearly, exclusively at casting porosity and fracture surfaces appear similar at low and elevated temperatures. Fatigue cracks may form at voids at stresses below the endurance limit, and non-propagating fatigue cracks of considerable length (greater 1 mm) are found in runout specimens. Considering porosity as an initial crack, critical stress intensity, \( K_{\text{crit}} \) is evaluated, which quantifies the sensitivity of a material to defects. Materials can sustain cyclic stresses without fatigue failure, if the cyclic stress intensity determined for their most damaging porosity is lower than \( K_{\text{crit}} \).

Keywords: Cast magnesium; Cast aluminium; Porosity; High-cycle fatigue; Endurance limit; Threshold stress intensity; Ultrasonic fatigue

1. Introduction

Magnesium alloys have received increased interest as possible construction materials in the automotive industry due to their low mass density, the possible benefit of weight reduction and consequently fuel saving. The rather high specific strength, the good castability and damping property, the improved corrosion resistance of high purity alloys and the possibility of recycling are additional advantages of these materials [1–3]. Today, cast magnesium alloys are used in several automotive applications like covers and doors, structures and heavier stressed components like wheels, housings and frames, for example. Effective weight reduction is possible using cast magnesium alloys progressively more often in load bearing components. Vehicles components are subjected to vibrations and repeated mechanical straining, and the number of load cycles may be very high, such as several 10\(^8\) cycles in car wheels. When magnesium alloys are considered for powertrain components, like crank case or gearbox casing, fatigue properties at elevated temperatures are of great interest and have to be compared to the cyclic properties of well-established cast aluminium.

Fatigue stress amplitudes in the range of 80 MPa at 10\(^8\) cycles and room temperature are reported for several cast magnesium alloys [4], which is closely comparable to cast aluminium alloys. These high fatigue strengths, however, are obtained with separately cast specimens, whereas the cyclic strength of material extracted from actually cast components may be significantly lower. Material defects act as starting places for fatigue cracks and deteriorate the fatigue behaviour of the cast. Early fatigue investigations already showed that porosity acts as main crack initiation place in cast magnesium [5,6].

Studying fatigue properties of AM50 alloy samples obtained from different places of prototype control arms and wheels showed that fatigue performance was significantly affected...
by the shrink and gas porosity at the extraction place [7]. Porosity as the source of fatigue cracks has been found in several investigations of AZ91, AM50 and AM60 [8–16]. Besides porosity, oxides [17] and Manganese-particle-enriched regions [18] may act as preferential sources of fatigue cracks in cast magnesium. Fatigue lifetimes are influenced by the size of the material defect, i.e. the larger the defect the shorter the fatigue lifetime [7,8,15,17]. The lower the cyclic load, the greater the influence of defects on fatigue properties. Cycling AZ91 T4 at strain amplitude $10^{-3}$, for example, led to lifetimes between $10^3$ and $5 \times 10^5$ cycles, depending on the defect size in the sample [17]. Thus, the fatigue properties of magnesium alloys are strongly influenced by the quality of the cast. Meaningful comparison of the cyclic properties of cast magnesium and aluminium requires testing both materials in conditions comparable to the intended technical application.

In a previous work [19], the fatigue properties at room temperature of high-pressure die-cast magnesium alloys AZ91 hp, AS21 hp, AE42 hp and AM60 hp have been compared to the aluminium alloy AlSi9Cu3, which is most frequently used in high-pressure die-casting in Germany. The materials were produced under conditions comparable to the casting of actual components. Porosity, which is inevitable in high-pressure die-casting, was most important for crack initiation and fatigue lifetime, and cracks, nearly, exclusively started at these material defects. All alloys showed an endurance limit in ambient air with maximum cycles to failure of about $2 \times 10^7$. Fracture mechanics principles were applied considering porosity as initial cracks. Failed specimens and runouts were evaluated to determine the so-called ‘critical stress intensity factor’ $K_{\text{crit}}$, which determines the maximum stress amplitude a material can sustain without fatigue failure in presence of porosity. This parameter was used to link the fracture probability with the distribution of defects in the cast materials.

Considering porosity as initial cracks is a well established method to model the fatigue behaviour of cast aluminium alloys, and fatigue lifetime may be considered as numbers of cycles necessary to propagate the crack to fracture [20–23]. Investigations on 319 T7 aluminium verified [24,25] that the crack initiation period at porosity is negligible and cracks may initiate even at stresses below the endurance limit. The larger the casting defect the shorter the crack extension period. Thus the observed fatigue lifetimes are inversely correlated to the size of the defect in constant amplitude [20–23] as well as in variable amplitude tests [26,27]. Recently, fracture mechanics concept has been similarly applied to predict lifetimes of cast magnesium AZ91 by integrating growth rates of cracks initiating at porosity [15].

In the present investigation, the fatigue properties of high-pressure die-cast magnesium alloys AZ91 hp, AS21 hp and AE42 hp are studied at elevated temperatures, and the aluminium alloy AlSi9Cu3 serves for comparison. Fatigue lifetime and crack growth experiments are performed and the obtained results are compared to the fatigue performance at room temperature. The aluminium alloy is tested at 150 °C. The magnesium alloys are cycled at the lower temperature of 125 °C due to their inferior creep resistance. However, this temperature is meaningful for several practical applications, in gearbox housings for example, where one of the alloys (AZ91) is actually used [28]. Mainly high cycle fatigue properties and near threshold fatigue crack growth behaviour are investigated. The endurance limit is determined at $10^8$ cycles, and maximum fatigue crack growth rates of $10^{-12}$ m/cycle are used to characterise threshold stress intensity. The experiments are performed using the ultrasonic fatigue testing method working at cyclic frequency 20 kHz. Previous experiments, though at room temperature, have shown that similar lifetimes are measured cycling at 20 and 50 Hz [19] and no pronounced effect of cyclic frequency on fatigue performance of these alloys may be expected therefore. Fracture surface studies and fracture mechanics considerations serve to evaluate the influence of porosity on fatigue properties.

### 2. Materials and procedure

#### 2.1. Materials

Fatigue properties of the aluminium alloy AlSi9Cu3 and the magnesium alloys AZ91 hp, AS21 hp and AE42 hp are investigated. The materials are produced by high-pressure die-casting at a solidification pressure of 60 MPa (AZ91 hp), 53 MPa (AE42 hp, AlSi9Cu3) and 30 MPa (AS21 hp), respectively. Table 1 shows the chemical compositions of the investigated alloys, and Table 2 summarises their static strength properties at ambient and elevated temperatures [29].

The materials are cast in bars with stepwise varying thickness. Specimens used in constant amplitude fatigue lifetime investigations (S–N tests) are shown in Fig. 1(a).

<table>
<thead>
<tr>
<th>Chemical compositions (in wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>AlSi9Cu3</td>
</tr>
<tr>
<td>AZ91 hp</td>
</tr>
<tr>
<td>AS21 hp</td>
</tr>
<tr>
<td>AE42 hp</td>
</tr>
</tbody>
</table>
These specimens are obtained from the bar at a thickness of 7.5 mm and 1.25 mm was removed from both sides to obtain the final specimen thickness of 5 mm. Edges in the centres of the specimens were rounded (radius 0.5 mm) and the surfaces were polished parallel to the specimen axis prior to the measurements with abrasive paper of grade 1000. Fatigue crack growth tests were performed using single edge notched specimens as shown in Fig. 1 (b). These specimens were obtained from the bar at a thickness of 15 mm. A notch was introduced by spark erosion and served to obtain a defined place for crack initiation.

2.2. Fatigue testing method

The ultrasonic fatigue testing method has been used to perform fatigue lifetime and fracture mechanics investigations at load ratio $R = -1$. Specimens are excited to resonance vibrations at a frequency of approximately 20 kHz, which leads to maximum vibration amplitudes at both specimen’s ends and maximum strain amplitudes in the specimen’s centre, i.e. at the place of the vibration node. Strain gauges are used to measure the cyclic strain and to calibrate the experiments. At one specimen’s end a vibration gauge serves to measure the vibration (displacement) amplitude, which is used to control the experiment. The displacement amplitude of the specimen is kept constant at the pre-selected magnitude with high accuracy (typically within ±1%). Specimens are not cycled continuously but in a sequence of pulses of 25 ms each (approximately 500 cycles) and pauses of adequate length (25–250 ms), since continuous cycling would increase specimen temperature due to internal friction. Stress amplitudes are calculated using the measured strain amplitudes and the Youngs’ moduli of the materials, i.e. 45 GPa at 20 °C and 41 GPa at 125 °C for the magnesium alloys [29] and 77 GPa at 20 °C and 71 GPa at 150 °C for AlSi9Cu3.

S–N experiments at elevated temperatures are performed, in principle, in a similar manner to the experiments in ambient air described previously [19]. The main experimental difference is that heated air

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_m$ (MPa) at 20 °C, 150 °C</th>
<th>$R_{p0.2}$ (MPa) at 20 °C, 125 °C</th>
<th>$A_5$ (%) at 20 °C, 150 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi9Cu3</td>
<td>216 (150 °C), 198 (150 °C)</td>
<td>134 (150 °C), 123 (150 °C)</td>
<td>1.0 (150 °C), 1.1 (150 °C)</td>
</tr>
<tr>
<td>AZ91 hp</td>
<td>190 (125 °C), 165 (125 °C)</td>
<td>118 (125 °C), 93 (125 °C)</td>
<td>3.6 (125 °C), 12.7 (125 °C)</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>131 (125 °C), 103 (125 °C)</td>
<td>84 (125 °C), 65 (125 °C)</td>
<td>2.1 (125 °C), 4.2 (125 °C)</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>184 (125 °C), 146 (125 °C)</td>
<td>101 (125 °C), 82 (125 °C)</td>
<td>5.0 (125 °C), 18.8 (125 °C)</td>
</tr>
</tbody>
</table>

Fig. 1. Specimen shapes used in (a) S–N tests and (b) fatigue crack growth tests.
provided by a hot air fan flows against the specimens. Specimen surface temperatures are controlled either with thermocouples or with temperature-dependent current sources and are kept constant at 150 °C (aluminium alloy) and 125 °C (magnesium alloys), respectively. Previously obtained S–N data of the alloys measured in ambient air of 18–22 °C and 40–60% relative humidity are shown for comparison.

Specimens were loaded until failure or at least 10⁷ cycles, if they did not fail (runnouts). At high cyclic stresses, where all tested specimens failed, power law functions of cyclic stress, σ and cycles to failure, N are used to approximate data (Eq. (1)):

\[ \sigma^k N = \text{const} \]  

A log normal distribution of cycles to failure is assumed to calculate 50% probability for failure. To evaluate the endurance limit at 10⁷ cycles, a procedure recommended by Maenning [30] is used. If \( i \) is the number of specimens failed below 10⁵ cycles and \( n \) is the number of specimens tested at this stress level, the probability for failure, \( P_f(\sigma) \) is calculated using Eq. (2):

\[ P_f(\sigma) = \frac{(3i - 1)}{3n + 1} \]  

The Probit function serves to approximate the probabilities for failure. The mean endurance limits at 10⁷ cycles (50% fracture probability below 10⁹ cycles) and their standard deviations are evaluated. Twenty-five specimens or more are used in each testing series to obtain statistically meaningful data.

Fatigue crack growth at elevated temperatures is studied by introducing the single edge notched specimens in warm airflow. Crack growth rates, \( \Delta a/\Delta N \) at certain cyclic stress intensity amplitude, \( K_{\text{max}} \) are measured by decreasing and increasing the stress intensity in 5–7% steps in successive experiments. Crack growth rates are determined as mean growth rates over crack length increments of 0.15–0.20 mm. Video equipment and magnification lenses serve to determine crack length on the specimen’s surface with a resolution of approximately 7 μm. If no crack growth is detected, cycling the specimen with at least 2 × 10⁷ cycles serves to determine threshold stress intensity. With the optical resolution, the maximum growth rate of 3.5 × 10⁻⁴ m/cycle is used to characterise threshold.

Previously performed fatigue crack growth experiments in ambient air (18–22 °C, 40–60% relative humidity) and in a vacuum (pressure ranges from 10⁻³ to 5 × 10⁻³ Pa) are included for comparison [31]. In ambient air, cycling the specimen for 2 × 10⁷ cycles served to determine threshold stress intensity, similar to the experiments in warm air. In vacuum, the threshold is determined loading the specimens with 10⁶ cycles to account for the lower optical resolution using a vacuum chamber [31]. Details of ultrasonic fatigue and fatigue crack growth experiments, determination of cyclic stress intensity and the evaluation of data are described elsewhere [32].

2.3. Evaluation of porosity

In the investigated alloys, nearly all fatigue cracks initiate at porosity (voids and shrinkage) [19]. To determine the size of material affected by porosity at the crack initiating place, fracture surfaces were examined using scanning electron microscopy (SEM). The projected area of the defect in specimen’s length direction (i.e. the direction of principal stress), termed ‘defect area’ is evaluated. Defect areas are evaluated for two purposes. It may be assumed that fatigue cracks initiate at one of the largest material defects in the stressed volumes of the specimen. Thus, the distribution of defect areas reflects the distribution of the largest material defects of the alloy, which characterises the quality of the cast and is most important for the fatigue properties of the material.

Considering porosity as an initial crack, fracture surface studies are used for fracture mechanics considerations. Murakami et al. [33] have shown that the stress intensity factor of a flaw is influenced by its shape by less than 10% and may be calculated considering solely the applied stress, the projected area of the flaw and its location. Assuming the area affected by porosity (Defect Area) as an initial crack, the stress intensity amplitude, \( K_{\text{max}} \) is calculated for \( R = -1 \) loading with Eq. (3)

\[ K_{\text{max}} = \sigma_{\text{max}} \alpha \sqrt{\pi \sqrt{\text{Defect Area}}} \]  

where \( \sigma_{\text{max}} \) is the cyclic stress amplitude, \( \alpha = 0.65 \) for surface defects (and for defects close to the surface [19]) and \( \alpha = 0.50 \), if the crack originates from internal porosity. If specimens failed, the stress intensity was sufficient to prolong the fatigue crack from the initial defect to rupture, whereas runouts either contained too small porosity or were stressed at too low stress amplitudes. To include runouts in the analysis, these specimens were fractured at higher stress amplitudes after low amplitude cycling. Fatigue data produced with runouts at the high stress are not included in the diagrams or in the evaluations of the endurance limits due to possible coaxing effects, and high stress cycling of runouts solely served to produce the fracture surfaces.

Calculating the stress intensity factors for failed specimens and runouts serves to quantify the lowest stress intensity factor necessary for fracture and the highest stress intensity where no failure occurred. The range between these two values is termed critical stress intensity amplitude, \( K_{\text{crit}} \) [19] and characterises the range where specimens may fail whereas others do not. The surfaces of some AlSi9Cu3 and AZ91 hp specimens which were cycled in warm air and did not fail within 10⁷ cycles were examined in the SEM using a rotating stage. This served to investigate non-propagating cracks in runout specimens.
### 3. Results

#### 3.1. S–N data

The results of constant amplitude lifetime investigations are presented in Fig. 2. Fatigue data measured at elevated temperatures are shown with closed circles, and previously measured data at ambient temperature [19] are included with open circles. Specimens which did not fail within minimum 10⁹ cycles (runouts) are marked with arrows. Two straight lines in the double logarithmic diagrams are used to characterise 50% fracture probability at elevated temperatures (solid lines) and at ambient temperature (dashed lines). Below 10⁶–10⁷ cycles, lines with constant slope indicate increasing mean lifetimes with decreasing cyclic stresses. The exponents \( k \) (Eq. (1)) are in the range from 6 to 8 for all four materials at both temperatures. Above approximately 2×10⁷ cycles, failures are rare, and data are approximated with lines parallel to the abscissa. No AlSi9Cu3 specimen (Fig. 2(a)), one AZ91 hp specimen cycled in ambient air (Fig. 2(b)), two AS21 hp specimens cycled in warm air (Fig. 2(c)) and one AE42 hp specimen cycled in warm air (Fig. 2(d)) failed at numbers of cycles greater than 2×10⁷.

Table 3 summarises the mean endurance limits and their standard deviation in warm and ambient air. Mean endurance limits decrease as the testing temperature increases. In AlSi9Cu3, the mean endurance limit at 150 °C is approximately 80% of the cyclic stress measured at 20 °C. The mean endurance limit of the magnesium alloys at 125 °C is approximately 90% (AZ91 hp), 70% (AS21 hp) and 85% (AE42 hp) of the respective stresses found in ambient air. Standard deviations of the mean endurance limit are not given.

Table 3

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean endurance limit ± standard deviation, warm air (MPa)</th>
<th>Mean endurance limit ± standard deviation, ambient air (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi9Cu3</td>
<td>61 ± 12</td>
<td>75 ± 14</td>
</tr>
<tr>
<td>AZ91 hp</td>
<td>41 ± 6</td>
<td>45 ± 7</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>27 ± 5</td>
<td>38 ± 8</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>35 ± 5</td>
<td>42 ± 9</td>
</tr>
</tbody>
</table>

Fig. 2. S–N data of (a) AlSi9Cu3, (b) AZ91 hp, (c) AS21 hp and (d) AE42 hp at ambient (open circles, dashed lines) and elevated temperatures (closed circles, solid lines).
limits of all materials are about 15–20% of the respective mean values in both environments. Specimens may fail in ambient air at stresses where others survived in warm air. The pronounced scatter in the cyclic properties is caused by material defects.

3.2. Fatigue crack initiation

Porosity plays a most important role for crack initiation and fatigue performance in the investigated alloys. Fatigue cracks in 105 of the 107 specimens fractured in warm air initiated at this kind of material defect. Large areas with porosity may lead to drastically reduced lifetimes. In AlSi9Cu3, one specimen cycled at 85 MPa failed after $1.0 \times 10^6$ cycles, whereas the other specimens stressed at this amplitude survived at least $5.7 \times 10^6$ cycles (Fig. 2(a)). Fatigue crack initiation area of this specimen is shown in Fig. 3. Close to the surface, voids created by gas porosity surrounded by dendrites and shrinkage porosity are visible. The defect area of this specimen is approximately 2.5 mm$^2$, which is the largest defect area found on fracture surfaces of all specimens. The damaging influence of this defect on the fatigue behaviour is caused by its large size and the location close to the specimen surface.

Defect areas at the crack initiation places of all specimens have been evaluated, and the size distributions are shown in Fig. 4. In Fig. 4(a), defect areas are classified in a histogram and Fig. 4(b) shows a probability diagram. The defect areas found on fracture surfaces of specimens ruptured in ambient air [19] are included to enlarge the statistical basis. The arithmetical mean and the maximum defect areas and the equivalent diameters, i.e. the diameter of a circle with the same area, are shown in Table 4. Defect areas range from 0.017 to 2.5 mm$^2$, and defects greater than 1 mm$^2$ could be detected in each material. AE42 hp contains, on average, the smallest defects. Defect areas in AS21 hp are, on average, approximately a factor of 1.7 larger than in AE42 hp.

![Fig. 3. Porosity visible on the fracture surface of AlSi9Cu3 specimen which was cycled at 85 MPa in warm air of 150°C and failed after $1.0 \times 10^6$ cycles.](image-url)
found on the surface of an AlSi9Cu3 specimen (Fig. 5) and on the surface of an AZ91 hp specimen (Fig. 6), respectively. The AlSi9Cu3 specimen was loaded with $1.05 \times 10^9$ cycles at 47.5 MPa, which is 78% of the mean endurance limit of this material in warm air. The AZ91 hp specimen was cycled at 38 MPa (90% of the mean endurance limit) for $1.51 \times 10^9$ cycles. Several SEM pictures of the specimens’ surfaces at different magnifications were taken to exactly locate the indicated crack tips. Afterwards, the specimens were removed from the SEM and fractured at higher cyclic stresses. This served to produce the fracture surfaces, which are shown at the same magnification in the lower part of Figs. 5 and 6. Gas porosity is the origin of both fatigue cracks. Crack length on the surfaces are 1.0 mm (AlSi9Cu3) and 1.6 mm (AZ91 hp). These crack lengths are considerably larger than the respective sizes of the crack initiating porosity. The longest cracks observed on surfaces of runnout AlSi9Cu3 specimens were 1.2 mm and were found on two specimens cycled at 47.5 and 57 MPa, respectively. The longest surface cracks of runnout AZ91 hp specimens were 1.6 mm (Fig. 6) and 1.2 mm after cycling at 38 MPa.

### Table 4

<table>
<thead>
<tr>
<th>Material</th>
<th>Mean Defect Area ($\text{mm}^2$)</th>
<th>Equivalent Diameter of the Mean Defect Area (mm)</th>
<th>Largest Defect Area ($\text{mm}^2$)</th>
<th>Equivalent Diameter of the Largest Defect Area (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi9Cu3</td>
<td>0.63</td>
<td>0.89</td>
<td>2.50</td>
<td>1.78</td>
</tr>
<tr>
<td>AZ91 hp</td>
<td>0.30</td>
<td>0.61</td>
<td>1.43</td>
<td>1.35</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>0.42</td>
<td>0.74</td>
<td>1.47</td>
<td>1.37</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>0.25</td>
<td>0.56</td>
<td>1.42</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Fig. 5. Non-propagating fatigue crack in AlSi9Cu3: the fatigue crack (upper figure) was visible on the specimen’s surface after cycling at 47.5 MPa for $1.05 \times 10^9$ cycles. Then the specimen was ruptured at 85 MPa in $1.15 \times 10^5$ cycles to produce the fracture surface (lower figure). Fatigue crack and fracture surface are at the same magnification, indicated on the upper figure.

Fig. 6. Non-propagating fatigue crack in AZ91 hp: the fatigue crack (upper figure) was visible on the specimen’s surface after cycling at 38 MPa for $1.51 \times 10^9$ cycles. Then the specimen was ruptured at 64 MPa in $1.30 \times 10^5$ cycles to produce the fracture surface (lower figure). Fatigue crack and fracture surface are at the same magnification, indicated on the upper figure.

### 3.3. Critical stress intensity amplitude

Assuming the area affected by porosity as the initial crack and using Eq. (3), the stress intensity amplitudes of all specimens were evaluated. Runnout specimens were fractured at high stresses to locate defects, which were too small to cause failure at the low loads. Stress intensity amplitudes of fractured specimens and runouts are shown in Fig. 7 with closed and open circles, respectively. Shaded areas indicate the ranges of the critical stress intensity factors, i.e. stress intensity amplitudes, which caused failure of some specimens and no failure of others. Table 5 summarizes the critical stress intensity factors at elevated temperature. Additionally, previously determined critical stress intensity factors in ambient air are shown. Mean values of the critical stress intensity factors in warm air are approximately 90% (AlSi9Cu3, AZ91 hp) or 80% (AS21 hp, AE42 hp) of the respective values found in ambient air. The ranges of
the critical stress intensity amplitudes in warm air are typically twice as large as in ambient air.

The fraction of fatigue cracks initiating at material defects at the surface is also shown in Table 5. In AlSi9Cu3, about 1/3 of the fatigue cracks initiated at surface porosity and 2/3 at internal defects in warm as well as ambient air. Crack initiation in the magnesium alloys in ambient air is preferentially at the surface, and 10% or less initiate from the interior. In warm air, this preference for surface crack initiation is less pronounced, and fatal fatigue cracks in approximately 25% (AZ91 hp, AE42 hp) or more (AS21 hp) of the fractured specimens initiated at internal porosity.

3.4. Fatigue crack growth and threshold data

In Fig. 8, the results of fatigue crack growth tests in warm air of 150°C (AlSi9Cu3, Fig. 8(a)) and 125°C (AZ91 hp, Fig. 8(b) and AS21 hp, Fig. 8(c)) are shown. For comparison, previously measured data in ambient air (open circles) and in a vacuum (triangles) are included [31]. Arrows indicate that no crack growth was observed within the optical resolution of crack length measurement cycling the specimens for $2 \times 10^7$ cycles (warm air and ambient air) or $10^8$ cycles (vacuum). These measurements indicate threshold stress intensities with limiting growth rates of $3.5 \times 10^{-13}$ m/cycle. Table 6 summarises the threshold stress intensity amplitudes at load ratio $R = -1$ in the three environments.

Increasing testing temperature leads to increased fatigue crack propagation rates and reduced threshold stress intensities in all three materials. Compared with ambient air, crack growth data measured in warm air are shifted towards lower stress intensity amplitudes. Threshold stress intensities at elevated temperatures are approximately 80% of the respective values found in ambient air. Minimum growth rates of propagating cracks in warm and ambient air are about $10^{-11}$ m/cycle (AlSi9Cu3), $10^{-10}$ m/cycle (AZ91 hp) and $3 \times 10^{-11}$ m/cycle (AS21 hp) and lower growth rates result from experiments, in which a crack propagated first and stopped afterwards, although stress intensity amplitude was kept constant. In vacuum, threshold behaviour in the magnesium alloys is not so distinct as in ambient or warm air, and cycling close to the threshold could produce mean fatigue crack propagation rates in the regime of $10^{-12}$–$10^{-11}$ m/cycle.

Fatigue fracture surface of AS21 hp after near threshold cycling at 20 and 125°C is shown in Fig. 9. The specimen was initially cycled in ambient air at constant stress intensity amplitude of 1.6 MPam$^{1/2}$. Then the experiment continued in warm air at the same stress intensity. Fig. 9 shows the area

<table>
<thead>
<tr>
<th>Material</th>
<th>Critical stress intensity amplitude in warm air, $K_{\text{crit}}$ (MPam$^{1/2}$)</th>
<th>Fraction of cracks starting at the surface, warm air</th>
<th>Critical stress intensity amplitude in ambient air, $K_{\text{crit}}$ (MPam$^{1/2}$)</th>
<th>Fraction of cracks starting at the surface, ambient air</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlSi9Cu3</td>
<td>1.4–1.8</td>
<td>0.37</td>
<td>1.75–1.95</td>
<td>0.33</td>
</tr>
<tr>
<td>AZ91 hp</td>
<td>0.85–1.05</td>
<td>0.72</td>
<td>1.0–1.1</td>
<td>0.92</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>0.55–0.75</td>
<td>0.56</td>
<td>0.7–0.8</td>
<td>0.96</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>0.7–0.9</td>
<td>0.76</td>
<td>0.9–1.1</td>
<td>0.90</td>
</tr>
</tbody>
</table>
on the fracture surface, where the environment has been changed from low temperature (left side of the figure) to elevated temperature (right side of the figure). Crack growth is transcrystalline, relatively flat and shows no apparent differences after cycling in both environments. The fracture surfaces of the other testing materials were also similar after cycling in ambient and warm air. Shrinkage porosity and dendrites are visible in the upper section of Fig. 9. Porosity is visible on several areas of the fracture surfaces and is probably the main reason for the pronounced scatter of fatigue crack growth data.

4. Discussion

Increasing the testing temperature deteriorated the fatigue properties of high-pressure die-cast magnesium alloys. S–N fatigue tests in warm airflow (125 °C) delivered endurance limits at $10^9$ cycles, which were 70–90% of the respective stresses found in ambient air (20 °C), and threshold stress intensities decreased to approximately 80% of the values found at the low temperature. Loss of cyclic strengths is within ranges comparable to the decrease of static strengths, since tensile strengths at elevated...
temperature are 80–85% and yield strengths are about 80% of the respective stresses found at ambient temperatures. Within the investigated magnesium alloys, AZ91 hp showed better cyclic properties in warm air than AE42 hp, and AS21 hp exhibited the lowest cyclic strength, which is the same ranking as in ambient air environment.

AlSi9Cu3 is a typical aluminium alloy used in high-pressure die-casting, and cyclic properties of the magnesium alloys may be compared with this material. Testing the aluminium alloy at 150 °C, fatigue limit and threshold stress intensity were about 80% of the respective values determined in ambient air. Deterioration of fatigue properties of the magnesium alloys by increasing the temperature to 125 °C is comparable to the loss of cyclic strength of the aluminium alloy by increasing the temperature to 150 °C. The mean fatigue limit of AZ91 hp at 125 °C is about 65% of the stress amplitude determined for AlSi9Cu3 at 150 °C, and threshold stress intensity is about 55% of the respective value of the aluminium alloy. The fatigue limits of the magnesium alloys at 20 and 125 °C are 40–45% of their respective yield stresses and 25–30% of the tensile strengths, whereas the fatigue limits of AlSi9Cu3 at low and elevated temperatures are 50–55% of its yield strength and 30–35% of the tensile strength.

Increase of temperature leads to greater cyclic plasticity involved with fatigue cycling [11], greater accumulated fatigue damage and thus lower cyclic strength of magnesium alloys [34,35]. Several aspects of the fatigue process at elevated and room temperature are, however, comparable. Fatigue cracks start, nearly, exclusively (more than 98%) at porosity in both environments. No obvious temperature influence on crack path and fracture surface appearance can be observed. Initial crack growth at porosity and crack propagation at near threshold stress intensities is mainly inside the (α-Mg) grains and tends to avoid interdendritic regions [19,31], which is consistent with the observations of Horstemeyer et al. [13] who found such crack paths cycling AM60-B and AZ91-T4 [17] at low stress intensity amplitudes. In contrast, at high cyclic stresses [36], at high temperatures of 250 °C [34] or stress intensities distinctly above threshold [13,17] cracks mainly initiate and propagate in the interdendritic region. The shapes of the S–N curves measured in warm air resemble the respective curves determined in ambient air environment, and increasing the testing temperature shifts the S–N curves towards lower cyclic stresses. In both environments, an endurance limit is found and cycles to failure above $2 \times 10^7$ cycles are rare.

Fatigue cracks were found on the surfaces of some specimens, which were cycled with minimum $10^7$ cycles and did not fail. These cracks may be assumed as non-propagating cracks, since possible mean growth rates to reach 1 mm within $10^7$ cycles would correspond to $10^{-12} \text{ m/cycle}$, which is below technical significance, at least in automotive applications. Comparable maximum lengths of non-propagating cracks are observed by Caton [24] who found crack length greater than 1 mm in 319 T7 aluminium specimens, which did not fail within $10^7$ cycles. In the magnesium alloy AZ91D, decreasing growth rates with increasing crack length and non-propagating fatigue crack are documented for cycling notched specimens at low stress amplitudes [37]. Stop of crack growth of fatigue cracks initiating at porosity may be explained by increasing crack opening stress intensity with increasing crack length [38], which eventually causes too low effective stress intensity ranges to further propagate the crack.

The endurance limit behaviour of the investigated materials is caused by porosity and the phenomenon of non-propagating cracks and is not an inherent property of the alloys. Testing AZ91 hp produced by gravity die-casting [8] and Vacural die-casting [19] and evaluating solely defect-free samples, considerably higher cyclic strength, monotonic increase of lifetimes with decreasing cyclic stresses and no endurance limit below $10^7$ cycles was found. Similarly, cast aluminium alloys frequently do not show a fatigue limit [4]. Thus, the endurance limit stress of the investigated alloys may be ascribed to the distribution of porosity and the capability of the microstructure to stop crack propagation. At low stress intensities, particles in the interdendritic region and grain boundaries may serve as barriers and decelerate fatigue crack propagation rates [17].

The critical stress intensity amplitude, $K_{\text{crit}}$, may be used as measure for the sensitivity of the microstructure to defects, i.e. the greater $K_{\text{crit}}$, the higher cyclic stresses are necessary to propagate a crack initiating at porosity to rupture. Specimens can sustain cyclic stresses without fatigue failure if the cyclic stress intensity determined for its most damaging porosity is lower than $K_{\text{crit}}$. Considering the distribution of porosity and the preference for crack initiation at the surface or in the interior, the probability for failure at certain stress amplitude may be linked to the distribution of porosity in a material [19].

![Ambient Air vs Warm Air](image-url)
Comparing the magnesium alloys, mean value of $K_{\text{crit}}$ of AZ91 hp in warm air is about a factor 1.45 higher than $K_{\text{crit}}$ of AS21 hp. The mean endurance limit of AZ91 hp is a factor 1.52 higher than the mean endurance limit of AS21 hp. Thus, the lower fatigue strength of AS21 hp is mainly caused by its greater defect sensitivity and to a far lesser extent by the greater mean defect size. On the other hand, mean defect size in AE42 hp is smaller than in AZ91 hp. Mean value of $K_{\text{crit}}$ of AZ91 hp is, however, about a factor 1.2 higher than $K_{\text{crit}}$ of AE42 hp, and consequently its mean fatigue limit is a factor 1.17 higher. Within comparable microstructures, the growth rates of small fatigue cracks increase as the yield strengths decrease [23]. This may be the reason for the correlation of $K_{\text{crit}}$ with the yield strength of the magnesium alloys, i.e. the higher the yield stress, the higher the critical stress intensity. $K_{\text{crit}}$ is lower than the threshold stress intensity of long cracks since short cracks grow at cyclic stress intensities below the long crack threshold [39]. Effective threshold stress intensities of AZ91 are found at 0.7 MPam$^{1/2}$ [40,41] and 0.55 MPam$^{1/2}$ [15], and $K_{\text{crit}}$ is larger than this value.

The greatest effect of testing temperature on the fatigue performance was found in endurance tests of AS21 hp, where the mean endurance limit at 125 °C is 71% of the stress found at 20 °C. A more pronounced influence of testing environment is observed comparing crack propagation properties in ambient air and vacuum. Threshold stress intensity of AZ91 hp in vacuum is a factor 1.55 higher than in ambient air, and a factor 1.85 higher threshold value in vacuum is found for AS21 hp. The deleterious influence of ambient air on fatigue damage in magnesium alloys is caused by air humidity, which accelerates crack growth and reduces the plasticity at the crack tip [42–45]. Chemical processes on the newly created surfaces are especially pronounced for near threshold cycling and slowly growing fatigue cracks [31]. Fatigue cracks form more rapidly and short cracks propagate faster if cycled in humid environment instead of in a vacuum [16]. In aluminium alloys, air humidity has a similar deleterious effect on fatigue crack growth [46–48]. However, compared with other aluminium alloys [49,50], the influence of atmospheric moisture on near threshold fatigue crack growth in AlSi9Cu3 is relatively small, and threshold stress intensity in vacuum is only a factor 1.3 higher than in ambient air.

In the absence of environmental effects, crack initiation location would be expected at the defect with the greatest value of $\alpha (\text{Defect Area})^{1/4}$, according to Eq. (3). However, fatigue cracks which initiate at surface defects grow under the influence of atmospheric moisture, whereas initial crack growth of internal cracks is in vacuum. In AlSi9Cu3, the deleterious influence of atmospheric moisture is relatively weak. Fatigue cracks preferentially initiate inside the specimen due to the greater probability that large defects are located in the interior of the stressed volume than at the surface. In the magnesium alloys, the stronger environmental effect causes preferential crack initiation at surface defects. In ambient air, crack initiation is almost exclusively (90% or more) at surface defects and the range of the critical stress intensity is narrow (Table 5). At elevated temperature, fatigue loading involves greater cyclic plasticity, which makes initiation of fatal cracks at (large) internal defects more probable. Minimum stress intensities necessary to propagate small cracks to fracture at 125 °C are probably different in inert environment and air. The greater variation of the crack initiation location is probably one reason for the wider range of the critical stress intensity at 125 compared with 20 °C.

5. Conclusions

The fatigue properties of the magnesium alloys AZ91 hp, AS21 hp and AE42 hp and of the aluminium alloy AlSi9Cu3 produced by high-pressure die-casting have been investigated in warm air. Experiments in ambient air served for comparison, and the following conclusions may be drawn.

1. Increasing testing temperature to 125 °C decreases the endurance limits of the magnesium alloys at 10$^9$ cycles to 70–90% of the stress amplitudes determined at room temperature, and the threshold stress intensities are about 80% of the respective values at 20 °C. Loss of fatigue strength of the aluminium alloy is in comparable ranges by increasing the temperature to 150 °C. Shapes of the S–N curves are similar at low and elevated temperatures and the curves are shifted towards lower cyclic stresses. Fatigue crack growth curves are shifted towards lower cyclic stress intensities.

2. The magnesium alloy AZ91 hp reaches about 2/3 of the endurance limit stress of AlSi9Cu3 and threshold stress intensities at low and elevated temperature are about 55% of the respective values of the aluminium alloy. AZ91 hp shows better cyclic properties than AE42 hp at room and elevated temperatures, and the lowest cyclic strength was found for AS21 hp, which corresponds to the ranking of the static strength properties of these alloys.

3. Fatigue crack initiation is, nearly, exclusively (greater 98%) at porosity in warm and ambient air and fatigue crack propagation is mainly transgranular. Fatigue cracks initiate at porosity even at stresses below the endurance limit. The longest cracks found on surfaces of specimens which survived 10$^9$ cycles were 1.0–1.6 mm. The endurance limit is related to a non-propagating condition of cracks rather than a non-initiating condition.

4. Considering the area affected by porosity as initial crack, failed and runnout specimens are used to determine the critical stress intensity amplitude, $K_{\text{crit}}$. Materials can sustain cyclic stresses without fatigue failure if the cyclic stress intensity determined for their most damaging porosity is lower than $K_{\text{crit}}$. The critical stress intensity amplitude is smaller than the threshold stress intensity of
long cracks and larger than the effective threshold stress intensity and can be used to quantify the sensitivity of a material to defects.

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References


