Influence of porosity on the fatigue limit of die cast magnesium and aluminium alloys

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Received 9 January 2002; received in revised form 1 May 2002; accepted 3 May 2002

Abstract

High cycle fatigue properties of high-pressure die-cast magnesium alloys AZ91 hp, AM60 hp, AE42 hp, AS21 hp and of similarly produced cast aluminium alloy AlSi9Cu3 have been investigated. Ultrasonic fatigue tests up to \(10^9\) cycles show mean fatigue limits of approx. 38–50 MPa (magnesium alloys) and 75 MPa (AlSi9Cu3) in the tested casting condition. Fatigue cracks initiated at porosity in 98.5% of the samples. Considering porosity as initial cracks, specimens fail, if critical stress intensity amplitude, \(K_{\text{cr}}\), is exceeded. \(K_{\text{cr}}\) of the magnesium alloys range from \(0.85\pm0.05\) to \(1.05\pm0.05\) MPa√m, and \(1.85\pm0.10\) MPa√m was found for AlSi9Cu3. Below \(K_{\text{cr}}\), fatigue cracks may initiate at porosity, however, do not propagate until failure. Using \(K_{\text{cr}}\), the statistical distribution of defects is linked to the fracture probability at different stress amplitudes.

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Keywords: Cast magnesium; Cast aluminium; Porosity; High-cycle fatigue; Fatigue limit

1. Introduction

Cast magnesium alloys have recently received increased attention as possible structural materials because of their low density and their rather high strength-to-weight ratio. Automotive applications are one of the possibilities where the benefits of weight reduction and, consequently, fuel saving is important [1,2]. Today, magnesium alloys are used in cars for low stress applications such as covers (e.g. camshaft covers, clutch housings, valve covers) and less frequently for mechanically loaded structural components such as wheels, transmission housings and pedals. Fatigue properties of materials used for stressed components have to be known, since cyclic loading rather than static loads may cause failure. The number of load cycles in automotive applications may be relatively high, i.e. car wheels are stressed at variable amplitude with several \(10^8\) cycles in service, and the high cycle fatigue properties are therefore of great interest. A compilation of S-N data of different cast magnesium alloys [3] shows fatigue limits of some alloys (on basis of \(10^8\) cycles) may exceed 80 MPa, which is in the range of several cast aluminium alloys, for example. However, the fatigue data of specially cast and heat-treated samples may not be typical for the quality obtained in cast components. Rather it is necessary to use the fatigue properties of magnesium alloys that are cast under conditions similar to the casting conditions for actual components. Several material defects, including porosity, oxide films or intermetallic inclusions [4] may facilitate fatigue crack initiation, reduce lifetimes and decrease the cyclic strength, especially at high numbers of cycles.

The present work addresses the high cycle fatigue properties of aluminium-containing magnesium alloys produced by high-pressure die-casting and their performance in comparison to similarly produced cast aluminium alloys. A main material defect in high-pressure die-cast components is porosity, which is caused by microshrinkage and by dissolved gases leading to voids. In cast aluminium alloys, the influence of porosity on fatigue behaviour has been addressed by several researchers [5–12] because of the prominent role of this kind of defect. High cycle fatigue investigations of aluminium cast alloy 356 showed that fatigue cracks predominately initiate at
voids, if their mean diameters are greater than approx. 50–100 µm [13–15]. This means that voids have to be considered as a main source of fatigue cracks for components produced by common casting techniques, such as sand casting or die-casting.

Lifetimes measured for materials containing porosity are typically subjected to increased scatter, since the cyclic properties of specimens depend on the sizes of eventual porosity and their location in the stressed volume, i.e. in the interior or at the surface. Several investigations of cast aluminium alloys show a distinct correlation of the size of porosity at crack initiation and the number of cycles to failure at constant load amplitude [5–7,12] as well as under variable amplitude loading conditions [9,11]. It has been generally assumed, that the stress concentration at pores or similar defects causes early crack initiation. Several investigations have confirmed this hypothesis and showed, that crack initiation life is negligible compared to cycles to failure, i.e. cracks are visible below 10^5 cycles although the specimen is cycled below the fatigue limit and did not fail during the next 10^8 cycles [12]. Models used to predict lifetimes of porous cast aluminium alloys determine the cycles necessary to propagate a crack from the initial defect size to fracture. Couper et al. [5] used linear elastic fracture mechanic principles, i.e. assuming a power law dependence of effective stress intensity range and crack propagation rate. Considering the effective threshold stress intensity and the stress concentration at porosity [6] as well as increased growth rates of short cracks [7,11] served to increase the accuracy of the calculations. Caton et al. [16] showed, however, that growth rates of small fatigue cracks in cast aluminium are not uniquely related to the effective cyclic stress intensity. Depending on stress amplitude and microstructure, short cracks may grow at lower or higher growth rates than assumed using the effective stress intensity range. Using a crack propagation law obtained from short crack growth studies, lifetimes of aluminium alloy 319 could be predicted with good accuracy [12].

Fatigue investigations of cast aluminium alloys mainly concentrate on the regime below approx. 10^7–10^8 cycles to failure. Recent investigations in the very high cycle regime show that fatigue properties at 10^9 cycles cannot be accurately predicted and lifetimes may be underestimated as well as overestimated when extrapolating from fatigue data obtained below 10^5 or 10^6 cycles [17]. Although some models of porous cast aluminium alloys assume a fatigue limit [5–7] experimental verification of this hypothesis above 10^6 cycles is limited [12]. Such investigations are necessary, since gravity die-cast aluminium cast alloy 356, for example, may [18] or may not [14] show a fatigue limit above approx. 10^8 cycles, depending on the actual amount of porosity.

Compared to cast aluminium alloys, studies of the fatigue properties of cast magnesium alloys are more limited [19–24]. Several investigations, however, show the prominent role of porosity acting as preferential crack initiation places [20–23]. Similar to cast aluminium, the number of cycles to failure for a given stress level can be correlated to the size of the porous area at the crack initiation place, i.e. the larger the defect area the lower the fatigue lifetime at a certain stress amplitude [14]. The deleterious influence of defects is especially pronounced at low cyclic stresses, where specimens containing large porosity may fail after 10^6 cycles, whereas others survive more than 10^9 cycles [21].

The present study examines the high and very high cycle fatigue properties of cast magnesium alloys AZ91 hp, AM60 hp, AE42 hp and AS21 hp and cast aluminium alloy AlSi9Cu3. All materials were produced similarly by high-pressure die-casting. The data shown will include 8 to 14 specimens of each material loaded with 10^9 cycles or more, which allows a determination of whether or not these alloys show a fatigue limit within this range. Testing several samples at very high numbers of cycles is possible using ultrasonic fatigue testing equipment working at a cycling frequency of 20 000 Hz [25]. With regards to apprehensions concerning eventual frequency influences on cyclic properties, the results are compared to fatigue data measured with conventional equipment at 50 Hz [26]. Fracture surface investigations of specimens, which failed below 10^6 cycles, are evaluated and compared to runouts, which were fractured afterwards at somewhat higher stress amplitudes. Assuming porosity as initial cracks, linear elastic fracture mechanics principles serve to establish a correlation between defect size and fatigue limit. This allows a combination of the statistical probability of different porosity size with the probability of failure at different stress levels.

2. Materials and procedure

2.1. Materials

Fatigue experiments have been performed with four magnesium alloys (AZ91 hp, AM60 hp, AE42 hp and AS21 hp) and one aluminium alloy (AlSi9Cu3) produced by high-pressure die-casting. To investigate the influence of porosity on fatigue lifetime, additional tests have been performed with AZ91 hp produced by Vacural die-casting, which leads to low porosity. Chemical compositions of the investigated alloys are shown in Table 1, and static strength properties and Vickers hardness (HV) are summarised in Table 2 [26]. HV have been measured with indentation force 613 N (62.5 kp) evaluating 10 indentations in each material.

Cast sheets with stepwise varying thickness were pro-
Table 1
Chemical compositions (in wt%) of the investigated materials

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Si</th>
<th>Ce</th>
<th>Fe</th>
<th>Cu</th>
<th>Ni</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91 hp</td>
<td>8.90</td>
<td>0.79</td>
<td>0.21</td>
<td>0.01</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>AM60 hp</td>
<td>6.10</td>
<td>0.01</td>
<td>0.29</td>
<td>0.01</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>AE42 hp</td>
<td>3.90</td>
<td>0.004</td>
<td>0.37</td>
<td>0.007</td>
<td>0.94</td>
<td>0.0003</td>
<td>0.001</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>AS21 hp</td>
<td>2.20</td>
<td>&lt;0.01</td>
<td>0.16</td>
<td>0.98</td>
<td>&lt;0.01</td>
<td>&lt;0.002</td>
<td>&lt;0.001</td>
<td>rem</td>
<td></td>
</tr>
<tr>
<td>AlSi9Cu3</td>
<td>1.2</td>
<td>0.1-0.4</td>
<td>8-11</td>
<td>1.0</td>
<td>2.0-3.5</td>
<td>0.1-0.5</td>
<td></td>
<td>0.1-0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
Ultimate tensile strength (Rm), yield stress (R_{p0.2}), fracture strain (A5) [26] and Vickers hardness

<table>
<thead>
<tr>
<th></th>
<th>Rm (MPa)</th>
<th>R_{p0.2} (MPa)</th>
<th>A5 (%)</th>
<th>Vickers hardness [HV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91 hp</td>
<td>190</td>
<td>118</td>
<td>3.6</td>
<td>65±2</td>
</tr>
<tr>
<td>AM60 hp</td>
<td>178</td>
<td>86</td>
<td>5.3</td>
<td>47±1.5</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>184</td>
<td>101</td>
<td>5.0</td>
<td>57±2</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>131</td>
<td>84</td>
<td>2.1</td>
<td>55±2</td>
</tr>
<tr>
<td>AlSi9Cu3</td>
<td>216</td>
<td>134</td>
<td>1.0</td>
<td>93±2.5</td>
</tr>
</tbody>
</table>

duced at a solidification pressure of 60 MPa (AZ91 hp), 53 MPa (AM60 hp, AE42 hp, AlSi9Cu3) and 30 MPa (AS21 hp). Specimens were from the bar at thickness of 7.5 mm, and 1.25 mm was removed by machining from both sides to obtain the final specimen thickness of 5 mm. The specimen shape is shown in Fig. 1. Edges in the centre 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 in order to obtain a well-defined surface finish.

2.2. Fatigue testing method

Fatigue experiments have been performed using the ultrasonic fatigue testing method. With this method, specimens are excited to resonance vibrations at a frequency of approx. 20 kHz. The vibration amplitude varies along the specimen axis, with maxima at the specimen’s ends. It becomes zero (vibration nodes) in the centre of the specimen and the cyclic strain amplitude shows a maximum there. Strain gauges serve to calibrate maximum cyclic strain amplitudes and to monitor the strain during the experiments. Using specimens as shown in Fig. 1, approximately a material volume of 0.27 cm$^3$ and a material surface of 1.86 cm$^2$ is cycled at tension-compression stresses greater than 95% of the maximum stress. Stress amplitude is calculated using the measured maximum strain amplitude and the Young’s modulus of the investigated materials, i.e. 45 GPa for the magnesium alloys and 77 GPa for the aluminium alloy. The experiment is controlled by measuring the vibration amplitude of one specimen end with a vibration gauge, and an accuracy of cyclic amplitude of typically ±1% is reached. Control of cycling frequency is necessary to track the actual resonance frequency of the specimen, which decreases when a fatigue crack initiates. Monitoring of the resonance frequency serves to stop the experiments when specimens fail.

The present investigations have been performed without superimposed load (load ratio $R=-1$). Specimens are loaded with pulses of 25 ms (approx. 500 cycles at a loading frequency of 20 kHz). Between the pulses pauses of adequate length serve to dissipate the heat caused by internal friction, and forced air-cooling is used additionally. Pause lengths were typically 25–250 ms and were chosen to assure that maximum the temperature of the specimens remained below 25 °C. Experiments were performed in ambient air (temperature 18–22 °C, relative humidity 40–60%). Details of the ultrasonic fatigue testing procedure and equipment are described in Ref. [25].

Specimens were cycled at constant amplitude until failure or until at least $10^8$ cycles were reached. In the regime below approx. $5 \times 10^7$ cycles, fatigue data of AZ91 hp, AM60 hp and AE42 hp of the same casting is available in the literature [26]. This allows comparing fatigue data obtained at 50 Hz and at ultrasonic frequency within this range.

2.3. Evaluation of porosity

Investigations of the crack initiation area using scanning electron microscopy (SEM) served to determine the
size of porosity (voids and shrinkage) at the crack initiation location. The projected area of these defects will be termed “defect area” in the following. Specimens, which did not fail (runnouts) were ruptured by increasing the cyclic stress amplitude to a stress level above the fatigue limit. This allows the study of defect areas, which are too small to cause failure at the initial stress level. Fatigue data for runnouts measured after the stress amplitude was increased are not included in S–N diagrams nor in data evaluation because of eventual coaxing effects.

Porosity evaluated with this technique shows a distribution of its maximum size in the stressed volume of the samples, since fatigue cracks mainly initiate at one of the largest voids. Evaluating porosity on polished surfaces, for example, underestimates the size of the largest porosity in a material [10,14]. Since the size of large porosity in a component is most important for its fatigue properties, this technique was used rather than evaluating global porosity or investigating polished surfaces. However, the distribution of defect areas does not show a distribution of all porosity sizes in the material but a distribution of sizes of the largest porosity.

Linear elastic fracture mechanics principles are used to evaluate the influence of porosity on the fatigue limit, and voids and shrinkage at the place of crack initiation are assumed as initial cracks. Murakami et al. [27] showed that the stress intensity factor mainly depends on the area of the flaw and its location and is influenced by its shape by less than 10%. With this assumption, the stress intensity amplitude, \( K_{\text{max}} \), is calculated for \( R = 1 \) [27] as

\[
K_{\text{max}} = \sigma_{\text{max}} \alpha \sqrt{\frac{\pi}{\text{Defect Area}}} \tag{1}
\]

where \( \sigma_{\text{max}} \) is the stress amplitude, \( \alpha = 0.65 \) for surface cracks and \( \alpha = 0.50 \) if the crack originates from internal porosity. To determine the defect area, the area of porosity at the crack initiation location is evaluated by SEM fractography. Porosity at the surface and close to the surface is considered as a surface crack, since the stress intensity increases as a flaw approaches a surface and growth toward the free surfaces is accelerated. To divide internal and surface porosity, a reasonable distinction for flaws close to the surface is necessary. The stress intensity of an elliptical flaw in a semi-infinite plate, where the distance to the surface is equal to its diameter, is less than 10% higher compared to a similar flaw in an infinite plane, depending on the shape of the flaw [28]. This increase of stress intensity is similar to the accuracy of Eq. (1) and the effect of the surface at this distance (or larger) is small. Porosity at a distance from the surface greater than or equal to half of its mean diameter is considered as internal porosity, whereas porosity located closer to the surface or at the surface is considered as surface porosity for the purpose of this study.

Using the stress intensity factor, it is assumed that a specimen fails if the stress intensity amplitude is sufficient to propagate the fatigue crack to fracture. Runnout occurs when the stress amplitude is too low or the defect area is too small to cause crack propagation to failure. By evaluating defect areas, defect location and stress amplitudes of failed specimens and runnouts it is possible to determine both the minimum stress intensity amplitude necessary to cause failure and the maximum stress intensity where a specimen did not fail. The term critical stress intensity amplitude, \( K_{\text{cr}} \), will be used in the following to characterise the regime between these two values, where some specimens may fail, whereas others do not. Below the critical stress intensity amplitude, fatigue cracks may initiate at porosity. However, they will not propagate to cause failure.

3. Results

3.1. S–N data

Fig. 2(a)–(e) show constant amplitude fatigue data of the investigated high-pressure die-cast materials. Arrows indicate runout specimens and solid lines show a fracture probability of 50%. AM60 hp and AZ91 hp show the best fatigue properties among the investigated magnesium alloys. AE42 hp shows slightly worse fatigue properties, and the lowest cyclic strength was found for AS21 hp. In the investigated regime of fatigue lifetimes, AM60 hp and AZ91 hp reach approx. 60–70% of the cyclic strength of AlSi9Cu3. All alloys show a pronounced fatigue limit, and failures beyond approx. \( 2 \times 10^7 \) cycles are rare. The mean fatigue limits are 45±10 MPa (AZ91 hp), 50±11 MPa (AM60 hp), 42±13 MPa (AE42 hp), 38±10 MPa (AS21 hp) and 75±18 MPa (AlSi9Cu3).

Fatigue cracks initiated at porosity in 98.5% of the investigated specimens. S–N data are subdivided into failures originating from surface defects (solid circles) and internal defects (open circles). In magnesium alloys, rupture is preferentially caused by fatigue cracks initiating at surface porosity, i.e. crack initiation of 92% of AZ91 hp specimen, 70% of AM60 hp, 90% of AE42 hp and 96% of AS21 hp specimen was at a surface defect (Table 3). In contrast, the fatigue failures of 67% of the AlSi9Cu3 specimens was caused by internal porosity.

In addition to ultrasonic fatigue data, the results of conventional fatigue tests at a cyclic frequency of 50 Hz [26] of AZ91 hp, AM60 hp and AE42 hp cast similarly by the same die-caster are shown in Fig. 2(a)–(c) with open triangles. Within the ranges of scatter, the fatigue lifetimes measured at both frequencies are similar, indicating that no significant influence of cyclic frequency on the lifetimes is observed. Previous investigations on wrought aluminium alloy 7075 [29], aluminium oxide particles reinforced alloy 6061 [30] and cast aluminium
Fig. 2. Fatigue data of (a) AZ91 hp, (b) AM60 hp, (c) AE42 hp, (d) AS21 hp and (e) AlSi3Cu3 produced by high-pressure die-casting. Solid circles refer to failure after surface or near surface crack initiation, and open circles indicate failure by cracks starting in the interior of the material. In (a) fatigue data of AZ91 hp produced by Vacural die-casting are shown with solid triangles. Open triangles in (a), (b) and (c) refer to fatigue data of similar material tested at 50 Hz [26].
Table 3
Critical stress intensity amplitudes, frequency of crack initiation at the surface and crack growth thresholds of long cracks in ambient air

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Critical stress intensity amplitude, $K_{cr}$ (MPa m$^{1/2}$)</th>
<th>Fraction of cracks initiating at the surface, $F_s$</th>
<th>Threshold stress intensity amplitude in ambient air, $K_{max,th}$ (MPa m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ91 hp</td>
<td>1.05±0.05</td>
<td>0.92</td>
<td>1.30–1.55</td>
</tr>
<tr>
<td>AM60 hp</td>
<td>1.075±0.075</td>
<td>0.70</td>
<td>1.40–1.55</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>1.0±0.10</td>
<td>0.90</td>
<td>–</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>0.85±0.05</td>
<td>0.96</td>
<td>1.25–1.45</td>
</tr>
<tr>
<td>AlSi9Cu3</td>
<td>1.85±0.10</td>
<td>0.33</td>
<td>2.45–2.70</td>
</tr>
</tbody>
</table>

alloy 319 [12] similarly showed no frequency influence and similar lifetimes in the high cycle regime if tested with ultrasonic and servo-hydraulic equipment.

In Fig. 2(a) the results of AZ91 hp produced by Vacural die-casting are included. These specimens showed significantly less porosity. Lifetimes for specimens where the fatigue crack did not initiate at porosity are included (as closed triangles) in the diagram. The S–N curve of Vacural die-cast material is shifted towards higher stress amplitudes and may be approximated by a straight line in a double logarithmic plot for the entire investigated regime from $10^5$ to $10^9$ cycles to failure.

3.2. Fractography

Several specimens, where voids were visible at the surface and which did not fail within $10^9$ cycles were investigated by scanning electron microscopy, and some showed fatigue cracks originating from these voids. Fig. 3 shows the surface of an AlSi9Cu3 specimen, which was cycled at 62 MPa and did not fail within $1.20 \times 10^6$ cycles. The fatigue crack has propagated to the indicated length but did not continue to grow to failure.

Fig. 4 shows two examples of porosity at crack initiation locations. In Fig. 4(a) the fracture surface of the only AZ91 hp specimen (of four specimens tested), which failed during cycling at 42 MPa is shown. The damaging effect of this pore is attributed to its large size and its location at the surface. In contrast, Fig. 4(b) shows at the same magnification the crack initiation area of an AM60 hp specimen, which did not fail at 52 MPa within $1.15 \times 10^9$ cycles. The defect area is smaller and the deleterious influence on the fatigue properties is less pronounced. The magnesium alloys show transcry stalline fatigue crack growth and a relatively smooth fracture.

Fig. 3. Fatigue crack initiating at a void at the surface of AlSi9Cu3. The specimen did not fail within $1.20 \times 10^6$ cycles.

Fig. 4. Porosity at the place of crack initiation in high-pressure die-cast AZ91 hp and AM60 hp. The AZ91 hp specimen (a) was cycled at 42 MPa and fractured after $1.92 \times 10^6$ cycles. The AM60 hp specimen (b) was stressed at 52 MPa and survived $1.15 \times 10^9$ cycles and was ruptured at 63 MPa afterwards.
surface, whereas the fracture surface of AlSi9Cu3 is rougher.

The projected areas of the critical defects from which fatal fatigue cracks initiated (defect areas) range from 0.025 to 1.63 mm$^2$. In Fig. 5 the defect areas and the mean diameters of the defects are classified in a histogram. Table 4 shows the mean sizes of defect areas as well as the maximum sizes of porosity found at crack initiation locations of the five materials.

### 3.3. Critical stress intensity amplitude

Using Eq. (1) and assuming porosity as an initial crack, the stress intensity amplitudes, $K_{\text{max}}$ of all tested specimens were evaluated. In Fig. 6 the stress intensity amplitudes calculated for broken specimens (solid circles) and runouts (open circles) are shown. The shaded regions indicate the regime of $K_{\text{cr}}$, i.e. where some specimens failed and others did not. The ranges of the critical stress intensity amplitudes are relatively close, as shown in Table 3. The largest variation was found for AE42 hp (1.0±0.1 MPa√m), which means an uncertainty of ±10%, whereas closer ranges were found in the other alloys.

The critical stress intensity amplitude can be used to correlate the most damaging porosity in a specimen to its critical stress amplitude, $\sigma_{cr}$. With the size of porosity (Defect Area) and its location (at the surface or in the interior) the critical stress amplitude is:

$$\sigma_{cr}(\text{Defect Area}) = \frac{K_{cr}}{\alpha \cdot \sqrt{\pi} \cdot \sqrt{\text{Defect Area}}}$$

The lower limit of $K_{\text{cr}}$ may be used to calculate the maximum stress amplitude the specimen can sustain without producing fatigue failure. The upper limit defines the minimum stress level required for fatigue failure within $10^9$ cycles. Between these two values it is uncertain whether the specimen fails or not.

Since the most damaging porosity in all specimens has been evaluated, the defect areas may be used for correlation with the fatigue limit. To establish a correlation between the distribution of defect areas and the probability for failure at specific stress amplitudes, the defect areas are statistically evaluated. In Fig. 7(a) and (b) the distributions of defect areas are presented in a log normal probability diagram. The ordinate indicates the probability of defect areas that are larger than the size indicated on the abscissa. The probability of occurrence of defect areas for the magnesium alloys is approximately linear indicating the existence of a log normal distribution. However, is less accurate to describe AlSi9Cu3 as a log normal distribution, but to compare the magnesium and aluminium cast alloys all materials were evaluated on the basis of the same distribution.

With the probability of occurrence, $p$ the defect area at the crack initiation location is greater than the defect area ($p$), as shown in Fig. 7. To calculate the stress amplitude with fracture probability $p$, $\sigma(p)$, the defect area ($p$), the critical stress intensity amplitude, $K_{cr}$ and the probability of crack initiation at the surface and in the interior, respectively are required. If all specimens fail either after crack initiation at the surface or all fail after crack initiation in the interior, respectively, $\sigma(p)$ can be calculated by:

$$\sigma(p) = \alpha \cdot \sqrt{\pi} \cdot \sqrt{\text{Defect Area}(p)}$$

If $F_s$ is the fraction of specimens that failed by crack initiation at surface porosity (Table 3) and $(1-F_s)$ is the fraction failed by internal porosity, $\sigma(p)$ is determined

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Mean and maximum diameter of area with porosity at the crack initiation site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean defect area (mm$^2$)</td>
</tr>
<tr>
<td>AZ91 hp</td>
<td>0.27</td>
</tr>
<tr>
<td>AM60 hp</td>
<td>0.23</td>
</tr>
<tr>
<td>AE42 hp</td>
<td>0.20</td>
</tr>
<tr>
<td>AS21 hp</td>
<td>0.26</td>
</tr>
<tr>
<td>AlSi9Cu3</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Fig. 6. Stress intensities of broken specimens (solid circles) and runnouts (open circles) assuming porosity at crack initiation as initial cracks. The shaded region indicates stress intensities, where failure as well as runouts occurred, i.e. critical stress intensity amplitudes.

by the weighted geometric average:

$$\sigma(p) = \left( \frac{K_{cr}}{0.65 \sqrt{\pi \sqrt{\text{Defect Area}(p)}}} \right)^{F_{s}}$$

$$\left( \frac{K_{cr}}{0.5 \sqrt{\pi \sqrt{\text{Defect Area}(p)}}} \right)^{(1-F_{s})}$$

In Table 5 the stress amplitude with fracture probabilities of 0.50, 0.20 and 0.05 are summarised.

4. Discussion

A most interesting result of the present investigation is the existence of a fatigue limit in the magnesium alloys AZ91 hp, AM60 hp, AE42 hp and AS21 hp and in the aluminium alloy AlSi9Cu3 if produced by high-pressure die-casting. Most specimens either fail below $2 \times 10^7$ cycles or they survive $10^9$ cycles or more. In fact, only two of 156 samples tested failed above $2 \times 10^7$ cycles. Cast aluminium and magnesium alloys frequently do not show a fatigue limit. Rather S–N curves show a monotonic increase of lifetimes towards lower stresses (although sometimes with reduced slope) below several $10^8$ [3] or several $10^9$ cycles [31].

The existence of a fatigue limit is not an inherent property of the investigated alloys but is caused by the casting procedure leading to relatively large porosity. Testing similar alloys without porosity, like Vacural die-cast AZ91 hp [Fig. 2(a)] or defect free gravity die-cast AZ91 hp [14] no fatigue limit below $10^9$ cycles was found.

Although a specimen did not fail within $10^9$ load cycles, fatigue cracks may have initiated at porosity, which is visible on the surface of some runout specimens. However, cyclic loading is too small to further propagate the crack when a certain length is reached. The existence of a fatigue limit in the investigated porous cast magnesium and aluminium alloys therefore appears to be caused by non-propagating fatigue cracks rather than by a non-initiation condition.
Fig. 7. Probability of occurrence of defect areas. The abscissa indicates the size of defect areas (and the respective mean diameters) and the ordinate shows the probability that specimens contain porosity larger than the indicated size in AZ91 hp, AS21 hp and AlSi9Cu3 (a) and in AM60 hp and AE42 hp (b), respectively.

By equating porosity area to the initial crack size, a calculation of the critical stress intensity of failed and unfailed specimens is possible. It should be noted that the mean stress in samples containing large areas with porosity is increased due to the reduction of sound cross section area. However, in the present study in compared to the cross section of the samples (35 mm²) the maximum cross section containing porosity (1.63 mm²) is relatively small and cannot explain the variation of cyclic properties of the different specimens. Rather the detrimental effect of porosity and its influence on fatigue lifetimes and fatigue limit is a consequence of longer or shorter initial cracks attributed to different porosity size.

Using $K_{cr}$, calculations of fracture probabilities at certain stress amplitudes are possible on the basis of the distribution of defects. In the present investigation, fracture probabilities (Table 5) have been calculated using the probability of occurrence of defect areas shown in Fig. 7. The probability diagrams have been obtained evaluating crack initiating porosity in fatigue samples and are influenced by both, the quality of casting and the stressed volume, i.e. larger stressed volumes increase the probability of large defects. If $K_{cr}$ and Eq. (4) is used to calculate stresses with different fracture probabilities of actual components, the maximum sizes of porosity in the respective stressed volumes have to be determined either experimentally (by X-ray studies, for example) or appropriately predicted by numerical casting simulations.

The values of $K_{cr}$ lie within a relatively close range in all investigated materials, which indicates a strong correlation between this parameter and eventual fracture of a specimen. This is remarkable, since inaccurate determination of the stress intensity using Eq. (1), disregarding the degree of porosity at the place of crack initiation and statistical scatter of crack propagation properties in grains of different orientation and different size adjacent to defect areas might influence the determination of $K_{cr}$.

The critical stress intensity amplitudes can be compared to threshold values of long fatigue cracks of the same alloys at a load ratio $R=−1$ (Table 3)[32]. The quantity of $K_{cr}$ of the investigated alloys is approx. 60–75% of the threshold stress intensity of long cracks. This means that a calculation of the fatigue limit on the basis of the threshold of long cracks would overestimate it. This is consistent with observations of short cracks, which may grow at cyclic stress intensities below the long crack threshold [33]. Effective stress intensity thresholds have been determined for a number of aluminium alloys and show a value between 0.8 and 0.9 MPa√m [34]. The effective threshold stress intensity of sand cast AZ91E-T6 has been determined to be approx. 0.7 MPa√m [35]. No experimental data were found in the literature for the other magnesium alloys. The critical stress intensities of high-pressure die-cast AZ91 hp and AlSi9Cu3 are higher than the effective thresholds. If the
critical stress intensity amplitudes found in the experiments are interpreted in terms of crack closure this means, that closure level of arrested cracks originating from porosity are lower than those of long cracks. The most frequent diameter of porosity of the investigated alloys is 0.50–0.88 mm (Table 4), which means that these cracks should be considered as short cracks. It is therefore plausible that the critical stress intensities are below the long crack threshold stress intensity.

The critical stress intensity amplitude may be used to compare the influence of defects on the investigated alloys. Statistical distributions of defect areas in AZ91 hp and AS21 hp [Fig. 7(a)] are closely similar. However, $K_{\text{b}}$ of AS21 hp (0.85±0.5) is approx. 20% lower than of AZ91 hp (1.05±0.05). By about a similar magnitude, the S-N curve of AS21 hp is shifted towards lower stresses, since porosity being more deleterious in AS21 hp. Obviously AS21 hp is less defect tolerant with respect to porosity when compared to AZ91 hp.

Several methods to treat defects in materials are described in the literature. Murakami and Endo [36] summarised different methods, which use the mean diameter of a defect or the square root of its projected area, (area)$^{1/2}$ for correlation with the threshold cyclic stress intensity of cracks originating from these defects, $\Delta K_{\text{th}}$, and with the fatigue limit, $\sigma_w$:

$$\Delta K_{\text{th}} \propto \left(\frac{\text{area}}{\text{area}}\right)^{1/6} \Rightarrow \sigma_w \left(\frac{\text{area}}{\text{area}}\right) = \text{const.} \quad (5)$$

They showed for different defect sizes in steels that $n=6$, if the defects are small (3–200 µm), whereas an exponent $n=3$ may better describe defects or notches larger than 100 µm [36]. The effect of small defects could be well predicted for a wide range of materials using Vickers Hardness (HV) and the area of the flaw (area, in µm²). Using $\beta=1.43$ for surface flaws and $\beta=1.56$ for internal defects the fatigue limit, $\sigma_w$ is [37]:

$$\sigma_w = \frac{\beta \cdot (\text{HV} + 120)}{\left(\frac{\text{area}}{\text{area}}\right)^{1/6}} \quad (6)$$

For the investigated magnesium alloys, however, a mean fatigue limit of 83–87 MPa would be predicted, which is approximately a factor of 2 higher than actually measured. The calculated mean fatigue limit of AlSi9Cu3 is expected at 103 MPa, which is approximately a factor of 1.4 higher than the experimental result.

The method used in this investigation implicitly used $n=2$ relating $K_{\text{th}}$ to stress amplitudes with different fracture probabilities and defect areas in Eq. (4). The relatively close regime of $K_{\text{th}}$ observed supports the usefulness of this concept for the investigated materials. The reasons for the validity of the concept are probably that (nearly) all fatigue cracks initiated at relatively large porosity and that the variation of porosity size at the crack initiation location is not too large (mean diameters vary from 0.18 to 1.40 mm). However, as defect sizes become smaller their deleterious influence on the cyclic strength will be greater than predicted on the basis of a stress intensity concept using $n=2$ [38]. The critical stress intensity amplitude may be used therefore to predict the (technically important) influence of large porosity on the fatigue limit, however, becomes invalid for small defect sizes. Moreover, assuming porosity as the only possibility of crack initiation would predict infinite fatigue strength of specimen produced by Vacuum die-casting, for example. Similar to cast aluminium alloys, fatigue cracks initiate at defects other than porosity or by slip in preferentially oriented grains if the size of porosity is small.

5. Conclusion

The fatigue properties of magnesium alloys AZ91 hp, AM60 hp, AE41 hp and AS21 hp and of aluminium alloy AlSi9Cu3 produced by high-pressure die-casting have been investigated in ambient air in the regime of $10^3$ to $10^9$ cycles.

- AZ91 hp and AM60 hp show the best fatigue properties among the investigated magnesium alloys. AE42 hp shows slightly worse fatigue properties, and the lowest cyclic strength was found for AS21 hp. AM60 hp and AZ91 hp reach approx. 60–70% of the cyclic strength of AlSi9Cu3.
- In 98.5% of specimens the fatigue crack initiated at porosity. The smallest area with porosity at crack initiation location was 0.025 mm² (mean diameter 0.18 mm). Porosity in magnesium alloys greater than this value may be considered as the most important

<table>
<thead>
<tr>
<th>Fracture probability</th>
<th>AZ91 hp</th>
<th>AM60 hp</th>
<th>AE42 hp</th>
<th>AS21 hp</th>
<th>AlSi9Cu3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>43–47</td>
<td>50–55</td>
<td>41–48</td>
<td>34–38</td>
<td>71–73</td>
</tr>
<tr>
<td>0.20</td>
<td>35–39</td>
<td>40–44</td>
<td>35–41</td>
<td>28–32</td>
<td>59–61</td>
</tr>
<tr>
<td>0.05</td>
<td>29–32</td>
<td>33–36</td>
<td>30–36</td>
<td>24–27</td>
<td>49–51</td>
</tr>
</tbody>
</table>

Table 5

Calculated stress amplitudes for different fracture probabilities using Eq. (4) (in MPa)
material defect for high cycle fatigue and fully reversed loading conditions.

- All investigated alloys show a pronounced fatigue limit. At the fatigue limit cracks may initiate at porosity but do not propagate to failure.

- If porosity is considered as equivalent to an initial crack, the fatigue limit can be correlated to critical stress intensity amplitude, \( K_{\text{cr}} \). The probability for failure at different stress amplitudes is determined by \( K_{\text{cr}} \), the probability of porosity to exceed a certain size (area) and the probability of crack initiation either at the surface or in the interior.

- Similar fatigue behaviour was found for cast magnesium alloys for tests conducted at 20,000 and at 50 Hz, indicating that ultrasonic fatigue testing is equivalent, for the test conditions examined, to standard low frequency testing.

Acknowledgements

Investigations were financed by the AUDI AG, Ingolstadt, which is gratefully acknowledged. The authors thank Prof J.W. Jones, Univ. of Michigan, for help preparing the manuscript.

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