Fatigue properties of the hot extruded magnesium alloy AZ31

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The fatigue properties of differently extruded magnesium alloy AZ31 and hence different microstructures were investigated during total strain and stress-controlled fatigue tests with different applied strain and stress amplitudes, respectively. Extruded magnesium profiles exhibit a significant asymmetry in the quasi-static mechanical properties under tension and compression, due to the low activation energy for the (10 1)(1 0 1) extension twinning. The asymmetry of the tension–compression yield strength leads to a sigmoidal shape of the hysteresis loops under cyclic loading conditions which is reduced if the tension–compression asymmetry is reduced. Moreover the evolution of stress and strain amplitudes, the plastic strain amplitudes and the mean stress and strain were analyzed. The Manson–Coffin and the Basquin approaches were used to describe the lifetime of the differently extruded products.

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1. Introduction

Based on its low-density magnesium alloys are attractive for applications in the field of lightweight constructions [1]. Up to now, cast alloys are used for most automotive applications. Nevertheless, wrought alloys are desirable for structural applications due to their enhanced mechanical properties, especially under fatigue conditions [2].

There are various studies about the macroscopic fatigue behavior of magnesium wrought alloys (e.g. [1–10]). Most of them concentrate on the description of the lifetime and the asymmetric deformation behavior due to twinning and the cyclic hardening behavior. The asymmetry of the hysteresis loops increases with the applied strain or stress amplitude. Higher strain or stress amplitudes result in stronger cyclic hardening behavior. It is reported that the lifetime could be well expressed in terms of the Manson–Coffin and Basquin approaches (e.g. [2,3]). The elastic strain amplitudes $\varepsilon_{A,el}$ (Eq. (1)) could be described by using the Basquin equation [11], the Manson–Coffin equation [12] describes the plastic strain amplitudes $\varepsilon_{A,pl}$ (Eq. (2)).

\begin{equation}
\varepsilon_{A,el} = \frac{\sigma}{E}(2N_f)^{-a}
\end{equation}

\begin{equation}
\varepsilon_{A,pl} = \epsilon'(2N_f)^{-b}
\end{equation}

$\varepsilon_A = \frac{\sigma}{E}(2N_f)^{-a} + \epsilon'(2N_f)^{-b}$

(3)

The parameters are the Young’s-modulus $E$, the fatigue strength coefficient $\sigma$, the fatigue strength exponent $b$ and the number of cycles to failure $N_f$. The fatigue ductility coefficient $\epsilon'$, and the fatigue ductility exponent $a$ are the parameters for the description of the plastic strain amplitude $\varepsilon_{A,pl}$.

The obtained low cycle fatigue parameters of other investigations [2,3,6,8,9] for differently processed magnesium alloy AZ31 are summarized in Table 1.

Also microstructural investigations on the formation of extension twins during compression [13], and the detwinning after load reversal and subsequent tensile loading were investigated by optical microscopy [14,15] and electron backscattered diffraction (EBSD) (e.g. [16,17]). The studies figured out, that the twins formed during compression disappear after subsequent tensile loading and smaller needle-shaped twins were formed.

The twinning–detwinning behavior during cyclic loading was also investigated by means of in situ neutron [18–20] and synchrotron X-ray diffraction [21,22], Brown et al. [18] and Wu et al. [19,20] reported for applied strain amplitudes of $\varepsilon_A = 1\%$ and $\varepsilon_A = 1.2\%$ that the total amount of twins in the compressive maximum increases with ongoing number of cycles $N$, while the detwinning mechanism under tension is progressively exhausted, resulting in an increase of residual twins in the tensile maximum of the hysteresis loop. In-situ diffraction studies with applied strain amplitudes $0.5\% < \varepsilon_A < 5\%$ [21,22] confirm the increase of residual twins in the tensile amplitude for all applied strain amplitudes $\varepsilon_A$, while the twinning activity in the compression maximum is a function of the applied strain amplitudes $\varepsilon_A$. In the regime 0921-5093/ – see front matter © 2010 Elsevier B.V. All rights reserved.
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of high applied strain amplitudes $\varepsilon_A > 0.7\%$ an increase in the twinning activity was observed, while applied strain amplitudes $0.5\% < \varepsilon_A < 0.7\%$ result in a decreasing twinning activity.

The asymmetry of the yield strength and the resulting twinning–detrwining mechanism are crucial factors to the fatigue of magnesium alloys [e.g. [2–4]]. In view of a systematical variation of the asymmetry of deformation, in the present study the influence of two modifications of indirect extrusion were investigated. The wrought magnesium alloy AZ31 was extruded conventionally as well as into counterpressure [23,24].

Total strain and stress-controlled uniaxial push–pull cyclic tests parallel to the prior extrusion direction were conducted at room temperature. The fatigue behavior, concerning the asymmetry of the hysteresis loops, the evolution of stress/strain amplitudes of the hysteresis loops, the evolution of stress/strain amplitudes, as well as the mean stress/strain temperature. The fatigue behavior, concerning the asymmetry of deformation, in the present study the influence of two modifications of indirect extrusion were investigated. The wrought magnesium alloy AZ31 was extruded conventionally as well as into counterpressure [23,24].

Table 1

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>Rolling</td>
<td>Extrusion</td>
<td>Extrusion</td>
<td>Extrusion</td>
<td>Extrusion</td>
</tr>
<tr>
<td>Grain size ((\mu m))</td>
<td>11</td>
<td>Up to 20</td>
<td>0.055–1</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Texture</td>
<td>(0 0 0 1)</td>
<td></td>
<td>RD</td>
<td>(0 0 0 1)</td>
<td></td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>5</td>
<td>0.1–1</td>
<td>1.49</td>
<td>1.03</td>
<td>1.37</td>
</tr>
<tr>
<td>$\sigma_{A}$ (MPa)</td>
<td>540</td>
<td>0.14</td>
<td>0.18</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>$\varepsilon_{f}$ (%)</td>
<td>6.65</td>
<td>69</td>
<td>0.41</td>
<td>1.89</td>
<td>1.78</td>
</tr>
<tr>
<td>$b$</td>
<td>5.02</td>
<td>0.79</td>
<td>0.69</td>
<td>0.39</td>
<td>0.40</td>
</tr>
<tr>
<td>Cyclic deformation behavior</td>
<td>Hardening ↑</td>
<td></td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>

2. Materials and experimental procedure

2.1. Specimens

Continuously cast AZ31 magnesium alloy billets were received from Otto Fuchs KG, Meinerzhagen. The chemical composition is presented in Table 2.

The extrusion tests for indirect extrusion with and without counterpressure (CP) were carried out on the ERDC at the Technische Universität Berlin.

The obtained material was processed by indirect extrusion either conventionally or with counterpressure [23,24]. A billet temperature $T_{b}=270$ °C, an extrusion ratio $R=25$ and a ram speed $v_{ram}=0.5$ mm s$^{-1}$ was chosen. For the characterization of the extruded profiles, metallographic and texture analyses were performed.

Samples for tensile (gauge length $l_g=40$ mm, diameter $D=8$ mm), compression ($l_g=20$ mm, $D=10$ mm) and cyclic ($l_g=16$ mm, $D=8$ mm) tests were machined parallel to the extrusion axis.

2.2. Experimental procedure

The samples for the microstructural characterization of the extruded profiles were prepared using the automatic grinding and polishing machine TegraPol-25. After grinding up to 4000 grit silicon carbide paper, polishing was carried out with 3 µm, 1 µm diamond paste and 0.2 µm silicon oxide. Finally, the samples were electropolished for 40 s with a voltage of 40 V and a flow rate of 12 (Struers Lectropol-5) using the commercial electrolyte AC2 (Struers). Afterwards the specimens were etched with picric acid solution containing 5 g picric acid, 6 ml acetic acid, 20 ml H2O and 100 ml ethanol.

The texture measurements were performed on the cross-sections of the extruded profiles using X-ray diffraction (Co Kα). For the texture analysis, the $\phi$ and $\psi$-scans were carried out for the (1 0 1 0), (0 0 0 2), (1 0 1 1), (1 0 1 2) and (1 2 0 2) planes using a collimator with a diameter of 2 mm. The inverse pole figures were then calculated from the ODF.

Both sample series (conventionally C; counterpressure CP) were investigated by tensile, compression and cyclic tests. All mechanical tests were conducted with the servo-hydraulic axial testing machine MTS 810. Both tensile and compression test used a strain rate of $2.5 \times 10^{-4}$ s$^{-1}$. The total strain/stress-controlled fatigue test were carried out at a strain ratio $S=\varepsilon_{min}/\varepsilon_{max}=-1$ or a stress ratio $R=\sigma_{min}/\sigma_{max}=-1$, respectively. A sinus-shaped testing curve was used and both strain and stress-controlled tests were realized at frequencies of $f=10$ Hz at room temperature. The strain amplitude $\varepsilon_A$ was varied between 0.3% and 0.75%, the stress amplitude $\sigma_A$ was varied between 130 and 210 MPa. The tests were carried out either until failure or up to $10^7$ cycles. To analyze the fracture morphology the SEM Jeol JSM 6400 was used.

3. Results

3.1. Microstructure and quasi-static mechanical properties

Fig. 1 shows micrographs which were taken from the longitudinal section. Both products show a dynamic recrystallized (DRX) grain structure with some elongated grains parallel to the extrusion direction. Extrusion with counterpressure results in a reduced grain size for the DRX grains. The reduced grain size is due to faster cooling conditions, which inhibit the static recrystallization (SRX) after the die [24]. EDS analysis revealed that the black dots are Al–Mn precipitations. The enormous size of the dots is due to preparation artifacts.

Both extrudates exhibit a typical (1 1 2 0) || (1 1 2 0) double fiber texture parallel to the extrusion direction (Fig. 2). Extrusion with counterpressure results in a decrease of the (1 1 2 0) pole density, while the (1 0 1 0) pole density increases. The reason for the lowered (1 1 2 0) fiber component is the hindered SRX due to faster cooling conditions. Similar results were also obtained by water-cooling after the extrusion process [25].

Generally extruded magnesium alloys exhibit a pronounced asymmetry of the yield strength under tension (TYS) and compression (CYS), due to the well known extrusion texture [23,25] and the low activation energy of the (1 0 1 2) || (1 0 1 1) twinning system.
when compressing along the extrusion direction (e.g. [26,27]). The extrusion with counterpressure (CP) results in a minor asymmetric behavior. The CP-series show significantly higher compression yield strength (CYS) compared to the C-series. The increased CYS results from a significant reduction of the average grain size $d$ of the recrystallized grains, which decreases from $d_\text{C} = 9\ \mu\text{m}$ to $d_\text{CP} = 4\ \mu\text{m}$, when extruded with counterpressure. More details about the analyses of the extrusion products concerning microstructure, texture and mechanical properties will be published in [24]. The results of the compression and tensile tests are summarized in Table 3.

### 3.2. Strain-controlled fatigue testing

In order to analyze the fatigue behavior the stress-strain hysteresis loops were measured for several different strain amplitudes $\varepsilon_A$. A significant influence of extrusion process could be observed. Especially during the first cycles the C-series shows an asymmetric sigmoidal-shaped hysteresis loop (Fig. 3a), which is normally observed for extruded magnesium alloys (e.g. [2–10]) at high applied strain amplitudes $\varepsilon_A$. This asymmetry is caused by the twinning under compression and detwinning after subsequent tensile loading [19–22]. On the other hand, the asymmetry is less remarkable for the CP-series (Fig. 3b) due to the higher CYS and a minor activation of the $\{10\overline{1}2\}/\{10\overline{1}1\}$ twinning system [28].

The asymmetric behavior is more pronounced, if the strain amplitude $\varepsilon_A$ is increased [3–6]. However, asymmetry decreases for both series during the fatigue test [7,8] due to cyclic hardening. At half-life $N/2$ the C-series still exhibits a sigmoidal-shaped hysteresis loop, while the CP-series shows a slight asymmetry only.

The plastic deformation is much higher for the C-series than for the CP-series. So, if the applied strain amplitude is set below $\varepsilon_A < 0.5\%$, there is little plastic deformation for the CP-series while the C-series still show significant plastic deformation. Consequently, the C-series exhibits an expanded hysteresis loop.

To analyze the cyclic hardening behavior in more detail, the evolution of the plastic strain amplitude $\varepsilon_{A,\text{pl}}$, the maximum stress $\sigma_{A,\text{max}}$ and the minimum stress $\sigma_{A,\text{min}}$ were registered during the entire fatigue test. The plastic strain amplitude $\varepsilon_{A,\text{pl}}$ as a function of number of cycles $N$ was calculated from the hysteresis loop. It was observed that the C-series shows cyclic softening during the first cycles, if loaded with high strain amplitudes $\varepsilon_A \geq 0.5\%$. Afterwards the C-series demonstrates pronounced cyclic hardening. On the other hand, the CP-series exhibits continuous, but less remarkable cyclic hardening. As shown by Begum et al. [3] the plastic strain amplitude remains nearly constant at low strain amplitudes. The plastic strain amplitude $\varepsilon_{A,\text{pl}}$ decreases about $\Delta \varepsilon_{A,\text{pl}} \sim 0.1\%$, if the C-series is loaded with $\varepsilon_A = 0.75\%$ and $\varepsilon_A = 0.625\%$. Under the same loading conditions, the plastic strain amplitude $\varepsilon_{A,\text{pl}}$ of the CP-series decreases only about $\Delta \varepsilon_{A,\text{pl}} \sim 0.03\%$.

The evolutions of the maximum stress $\sigma_{A,\text{max}}$ and the minimum stress $\sigma_{A,\text{min}}$ confirm these results. Based on the higher TYS, the CP-series shows an initially higher maximum tensile stress (Fig. 4). The cyclic softening observed during the first 10 cycles is caused by the inaccurate control of the strain parameter with the testing machine used. Afterwards both sample series show cyclic hardening. Never-

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**Table 3**

Mechanical properties of extruded AZ31 (loading direction || extrusion direction).

<table>
<thead>
<tr>
<th></th>
<th>C-series</th>
<th>CP-series</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% tensile yield strength TYS (MPa)</td>
<td>$-112 \pm 4$</td>
<td>$-159 \pm 5$</td>
</tr>
<tr>
<td>0.2% compressive yield strength CY (MPa)</td>
<td>$-112 \pm 4$</td>
<td>$-159 \pm 5$</td>
</tr>
<tr>
<td>Tensile Young’s modulus (GPa)</td>
<td>$40 \pm 1$</td>
<td>$40 \pm 1$</td>
</tr>
<tr>
<td>Compression Young’s modulus (GPa)</td>
<td>$37 \pm 2$</td>
<td>$38 \pm 2$</td>
</tr>
<tr>
<td>Ultimate tensile strength UTS (MPa)</td>
<td>$259 \pm 4$</td>
<td>$278 \pm 6$</td>
</tr>
<tr>
<td>Tensile fracture strain $\varepsilon_{A,\text{fr}}$ (%)</td>
<td>$23 \pm 1$</td>
<td>$23 \pm 1$</td>
</tr>
<tr>
<td>Ultimate compressive strength UCS (MPa)</td>
<td>$-398 \pm 7$</td>
<td>$-431 \pm 8$</td>
</tr>
<tr>
<td>Compressive fracture strain $\varepsilon_{C,\text{fr}}$ (%)</td>
<td>$-10.9 \pm 0.3$</td>
<td>$-11.2 \pm 0.3$</td>
</tr>
</tbody>
</table>
theless, a more pronounced cyclic hardening could be observed for the C-series in the tensile maximum (maximum stresses $\sigma_{A,\text{max}}$). As a result, the C-series reaches higher tensile stress levels at half-life $N_f/2$ compared to the CP-series. If the specimens of the C-series are loaded with a strain amplitude $\varepsilon_A = 0.75\%$, the maximum tensile stress $\sigma_{A,\text{max}}$ increases 23% between the second cycle and the rupture. Also for applied strain amplitudes $\varepsilon_A = 0.5\%$ a significant cyclic hardening was observed. In this case, the tensile stress $\sigma_{A,\text{max}}$ increases about 11%. If the strain amplitude is set below $\varepsilon_A = 0.5\%$, no significant hardening was noticed in the tensile maximum.

The cyclic hardening of the minimum compressive stresses (minimum stress $\sigma_{A,\text{min}}$) exhibits a similar behavior. Again, the C-series exhibits a stronger cyclic hardening behavior, which is the result of the lower CYS and the higher twinning–detwinning activity. Based on the higher plastic deformation of the C-series, $\sigma_{A,\text{min}}$ rises about 25%, if the strain amplitude is set between $\varepsilon_A = 0.75\%$ and $\varepsilon_A = 0.625\%$. Cyclic hardening in the compressive maximum was observed down to $\varepsilon_A = 0.3\%$.

The asymmetric deformation and cyclic hardening behavior of the investigated specimens results in a continuously increasing mean stress $\sigma_M$. It was observed that a significant mean stress $\sigma_M$ was build up [2,5] for applied strain amplitudes $\varepsilon_A > 0.625\%$. Based on the asymmetry of the yield strength, the mean stress is much higher in the case of the C-series. If the resulting total stress amplitude $\sigma_A$ is smaller than the yield strength, asymmetric deformation behavior is less notable.

3.3. Stress-controlled fatigue testing

Stress-controlled fatigue tests were carried out for applied stress amplitudes $120 \text{ MPa} \leq \sigma_A \leq 210 \text{ MPa}$. In order to analyze critical
changes in the deformation behavior the hysteresis loops shown in Figs. 5 and 6 are of particular interest.

Fig. 5 represents stress amplitudes $\sigma_A$ above the TYS and the CYS of both series. Fig. 6 shows the importance of the compressive yield strength. The here presented stress amplitude $\sigma_A$ is chosen lower than the CYS of the CP-series and higher than the CYS of the C-series.

Due to the experimental procedure, the default applied stress amplitude $\sigma_A$ was not realized correctly until $N = 30$ was reached. However, there are significant differences between both series. It can be seen, that the hysteresis loop is much more widened in the case of the C-series. Within one series, the hysteresis loops broaden with increasing applied stress amplitude $\sigma_A$. Furthermore, a drift of the hysteresis loop to a compressive mean strain was detected at high stress amplitudes $\sigma_A$ (Fig. 5). This cyclic creep behavior was also reported by [2,6]. The pronounced drift of the hysteresis loop could only be observed, if the stress amplitude $\sigma_A$ is higher than the CYS.

The detailed evolution of the mean strain is given in Fig. 7. In addition to the pronounced mean strain development during the first cycles, cyclic creep was found, which was also observed by Hasegawa [6].

The CP-series does not develop a significant compressive mean strain $\varepsilon_M$ if the stress amplitude $\sigma_A$ is set below 200 MPa. However, a slight tensile mean strain $\varepsilon_M, t$ was observed for $\sigma_A < 200$ MPa. In contrast, the C-series builds up a significant compressive mean strain $\varepsilon_M, c$ if the stress amplitude $\sigma_A$ is higher than 130 MPa. Furthermore, the C-series reaches about two times higher compressive mean strains $\varepsilon_M, c$ for $\sigma_A = 200$ MPa.

In order to display the influence of the stress amplitude $\sigma_A$ on the cyclic hardening process, the progression of the resulting total strain amplitude $\varepsilon_A$ is shown in Fig. 8. The $\varepsilon_A$ presented here was
calculated as follows:

$$\varepsilon_A = \frac{\varepsilon_{A,\text{max}} - \varepsilon_{A,\text{min}}}{2} \quad (4)$$

Both series exhibit continuous cyclic hardening (decrease of \(\varepsilon_{A,\text{pl}}\)) once the control stress amplitude \(\sigma_A\) is reached correctly \((N = 30)\). The only exception is given at \(\sigma_A = 200\) MPa in the case of the C-series, which shows continuous cyclic softening. The reason for this phenomenon is the combination of a high stress amplitude \(\sigma_A\) at \(f = 10\) Hz and the enormous resulting \(\varepsilon_A\), which results in a heating of the sample and consequently lowered strength. The cyclic hardening of the C-series is more pronounced for a given \(\sigma_A\).

In order to reveal the influence of the applied stress amplitude \(\sigma_A\) on the specific cyclic hardening in the tension and compression maxima, the evolution of the maximum strain amplitude \(\varepsilon_{A,\text{max}}\) and the minimum strain amplitude \(\varepsilon_{A,\text{min}}\) was studied. The strong decrease of the compressive mean strain \(\varepsilon_{M,c}\) for the C-series results in negative tensile strains \(\varepsilon_{A,\text{max}}\) and a strong decrease of \(\varepsilon_{A,\text{min}}\). The CP-series show almost no decrease of the compressive mean strain \(\varepsilon_{M,c}\) resulting in a constant evolution of \(\varepsilon_{A,\text{max}}\) and \(\varepsilon_{A,\text{min}}\).

### 3.4. S–N-curve

S–N-curves for both strain and stress-controlled fatigue tests give evidence that in the case of strain-controlled testing a tendency towards a higher lifetime of the CP-series can be observed, due to the improved CYS and less plastic deformation at the same values of \(\varepsilon_A\). However, stress-controlled tests showed a more complex result. Due to the improved TYS and CYS the CP-series shows higher numbers of cycles \(N\) at high stress amplitudes \(\sigma_A > 180\) MPa. Nevertheless, the C-series reaches a higher lifetime, if the stress amplitude \(\sigma_A\) is set below 170 MPa, which probably is the consequence of the different evolution of the observed mean strains \(\varepsilon_M\).

In order to obtain the parameters of the Manson–Coffin and Basquin-type equations, the plastic strain amplitude \(\varepsilon_{A,\text{pl}}\), the elastic strain amplitude \(\varepsilon_{A,\text{el}}\) and the total strain amplitude \(\varepsilon_A\) at \(N_f/2\) were plotted (Fig. 9). The S–N-curve for the strain-controlled tests was supplemented with data (very high \(\varepsilon_A\)) obtained from previous studies [28], and the whole set of data was taken for the evaluation.

So in both cases the description of plastic deformation requires a bilinear Manson–Coffin approach [5], which is valid for both series at very high applied strain amplitudes \(\varepsilon_A > 0.6\%) or applied stress amplitudes \(\sigma_A > 180\) MPa. The obtained LCF-parameters of the Manson–Coffin approach for very high loads are unusually high. This may be explained by the fact, that twinning is the predominant deformation mechanism in the high plastic deformation regime, while dislocation glide is the predominant mechanism in the low plastic deformation regime [5]. Also the differences in twinning activity support the bilinear plastic deformation behavior [28]. The evaluated LCF-parameters for both strain and stress-controlled fatigue tests are similar for very high loading conditions. A comparison of the obtained LCF-parameters for very high loads with other investigations [2–3] is not reasonable due to the different ranges of the applied strain/stress amplitudes.

But the parameters obtained from the Manson–Coffin equation for the lower strain/stress regime below \(\varepsilon_A < 0.6\%\) and below \(\sigma_A < 170\) MPa are in good agreement with the results reported in the literature [2–4,6–9] for both testing conditions. When comparing the fatigue parameters obtained by the different loading conditions only slight differences were observed. Table 4 summarizes the obtained parameters.

### 3.5. Fractography

Fracture surfaces of the specimens were examined using SEM and contain the fatigue crack initiation (white line) at the surface, crack propagation (black line) and final fast rupture. Typical images of the CP-series taken at low magnification are shown in Fig. 10. Fatigue cracks initiated mainly from the specimen surface [3,8]. Subsurface crack initiation occurred rarely [29], only if low stress/strain amplitudes were applied and hence a high number of cycles was achieved (Fig. 10a). These cracks initiated at inner defects such as voids or intermetallic Al–Mn particles. As seen from Fig. 10, the area of fatigue crack propagation increased with decreasing total strain amplitude \(\varepsilon_A\), because of the decreasing plastic strain amplitude [8]. No significant differences

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**Table 4**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\varepsilon_A)-Controlled (N=10^3) to (5 \times 10^3)</th>
<th>(\varepsilon_A)-Controlled (N&gt;5 \times 10^3)</th>
<th>(\sigma_A)-Controlled (N=10^3) to (5 \times 10^3)</th>
<th>(\sigma_A)-Controlled (N&gt;5 \times 10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_f/E) (%)</td>
<td>1.5</td>
<td>1.5</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>(a)</td>
<td>0.12</td>
<td>0.12</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>(\varepsilon_f) (%)</td>
<td>260</td>
<td>4.0</td>
<td>260</td>
<td>7.5</td>
</tr>
<tr>
<td>(b)</td>
<td>0.96</td>
<td>0.42</td>
<td>0.89</td>
<td>0.49</td>
</tr>
</tbody>
</table>
in the fracture surfaces were observed for the different sample series.

4. Discussion

4.1. Quasi-static mechanical properties

Quasi-static testing results have shown that extrusion into counterpressure results in increased TYS and CYS. Due to the hydrostatic medium, the extrusion product is cooled more rapidly, which results in a reduction of the average grain size \(d\) [24,25,30].

According to the Hall–Petch relation, the grain size \(d\) is crucial to the mobility of dislocations, but the Hall–Petch slope for the activation of the (112)/(1011) twinning systems is three times higher (e.g. [24,25]). Due to the smaller average grain size \(d_{\text{CP}}\) of the CP-series the critical resolved shear stress (CRSS) for twinning increases, which results in enhanced mechanical properties [25,31]. The counterpressure process also influences the texture. The (1120) fiber component is smaller than in the samples of the C-series. This result is also due to the interrupted SRX, since the (1120) fiber component increases during SRX [24]. But the differences are small, so the influence of the texture on the overall mechanical properties is not very pronounced.

4.2. Strain-controlled fatigue testing

Due to the increased CYS of the CP-series the asymmetry of the deformation behavior decreases. The obtained hysteresis loops exhibit a less pronounced sigmoidal shape. Due to the improved mechanical strength, the CP-series shows smaller plastic strain amplitudes \(\varepsilon_{A,\text{pl}}\) than the C-series. The higher \(\varepsilon_{A,\text{pl}}\) results in a more pronounced cyclic hardening of the C-series.

The plastic deformation at high \(\varepsilon_A > 0.6\%\) is dominated by twinning–detwinning and the total amount of twins and residual twins increase as a function of \(N\) [18–22]. Interactions between twin boundaries and dislocations result in cyclic hardening in the tension and compression maxima. At strain amplitudes \(\varepsilon_A \leq 0.5\%\) almost no plastic deformation has to be realized. Consequently, no significant cyclic hardening was observed.

As the fatigue damage is mainly a consequence of the plastic deformation [12,31], higher CYS of the CP-series enables higher numbers of cycles to failure \(N_f\).

The lifetime could be well expressed using a Basquin and a bilinear Manson–Coffin approach. Within the statistical limits both sample series could be described using the same parameters. At \(\varepsilon_A > 0.6\%\) a very high fatigue ductility exponent \(\varepsilon_f = 260\%\) was determined. The LCF-parameters obtained at \(\varepsilon_A \leq 0.5\%\) are within the scattering band of data given by other authors.

4.3. Stress-controlled fatigue testing

As described above the asymmetric deformation behavior is crucial to the fatigue properties of extruded magnesium alloys. Due to the inferior mechanical properties of the C-series the hysteresis loop exhibits an important broadening. At high stress amplitudes \((\sigma_A > 200\text{MPa})\) the hysteresis loops show continuous broadening until the failure of the specimen. That means, cyclic softening was observed during the entire lifetime. If \(\sigma_A\) is set below the TYS and higher than the CYS (transition zone), pronounced cyclic hardening was observed. However, the cyclic hardening gets less pronounced, if \(\sigma_A\) is reduced. The hardening progression can be described analogous to the mechanism in strain-controlled testing.

Applying stress amplitudes \(\sigma_A\) below both yield strengths, no significant cyclic hardening was observed. The reason is that almost no plastic deformation is required.

Cyclic hardening behavior for high \(\sigma_A\) is observed for both series. But the \(\sigma_A\) threshold for the transition regime is dependent on the quasi-static mechanical strength of the samples.

In addition to the cyclic hardening process a significant mean strain development was observed for the C-series. If the stress amplitude \(\sigma_A\) is set higher than TYS and CYS, both series exhibit a compressive mean strain progression. This progression can be explained by the asymmetric deformation behavior. The CYS is lower than the TYS. Consequently, a given stress amplitude \(\sigma_A\) results in a higher strain in the compression half-cycle, than in the tensile half-cycle. According to the deformation asymmetry a compressive mean strain \(\varepsilon_{M,c}\) is mandatory. Due to the lower tension–compression asymmetry, a smaller compressive mean strain \(\varepsilon_{M,c}\) was observed for the CP-samples.

Even though the deformation behavior of both series was qualitatively similar at \(\sigma_A = 200\text{MPa}\), there is a difference in the transition zone. The CP-series exhibits minor tensile mean strains \(\varepsilon_{M,t}\), while compressive mean strains \(\varepsilon_{M,c}\) were observed in the case of the C-series. This difference can be again explained by the stronger asymmetry of the yield strengths. Because of the higher TYS, the tensile deformation is still elastic, while the maximum compressive stress results in plastic deformation. This unilateral plastic deformation causes a contraction of the specimen, which increases during the cyclic testing. If the stress amplitude \(\sigma_A\) is lowered the compressive deformation decreases. Consequently, the contraction decreases as well as the mean strain \(\varepsilon_M\).

At low applied stress amplitudes \(\sigma_A\) the deformation asymmetry becomes weaker. Therefore, slight tensile mean strains were observed for the CP-series.

Furthermore, the S–N-curves were obtained from the recorded data at half-life \(N_f/2\) (Fig. 9). The lifetime could be well expressed using a bilinear Manson–Coffin and a Basquin’s approach. Within the statistical limits both sample series could be described using
similar parameters. The LCF-parameters obtained at $\sigma_A < 170$ MPa are within the scattering range of data reported by other authors [2,9]. At $\sigma_A > 180$ MPa a very high fatigue ductility exponent $\varepsilon'_f = 260\%$ was detected, which may be explained by two reasons. First the influence of twinning and detwinning becomes predominant for the cyclic deformation. Also the increase of the compressive mean strain $\varepsilon_{M,c}$ as a result of the twinning/detwinning behavior, influences the ductility exponent $\varepsilon'_f$.

4.4. Fractography

The analyzed fracture surfaces exhibit three different areas. Crack initiation is characterized by a smooth fracture zone, which is mostly located near the surface of the specimen [3,32]. High applied loads generate more crack initiation. Subsequently, a rougher transition zone was observed which can be related with the crack propagation process. The size of this crack propagation zone increases, if the strain or the stress amplitude is decreased, because of more stable crack propagation behavior. The third zone exhibits a rough surface caused by the overload rupture.

In some cases crack initiation is located in the bulk material, if only small loads were applied and hence high numbers of cycles $N$ were reached. This failure mechanism is related to inner defects such as voids and intermetallic Al–Mn particles.

5. Conclusions

Strain and stress-controlled fatigue tests of an extruded AZ31 alloy were carried out. A comparison of the fatigue behavior of indirect extruded profiles, extruded conventionally or into a counterpressure was performed. The following conclusions were drawn:

- Due to the counterpressure process, the mechanical properties of the extruded alloy were improved mainly by a grain size reduction. Especially the CYS increased significantly, which causes an important reduction of the asymmetry of deformation.
- Based on the improved quasi-static mechanical properties the CP-series exhibits a minor asymmetric, sigmoidal-shaped hysteresis loop. Furthermore, the broadening of the hysteresis loop was significantly reduced in comparison to the C-series. The improved quasi-static mechanical properties of the CP-series cause slightly higher lifetimes under strain-controlled testing conditions. As cyclic hardening is related to the plastic deformation, it is much more pronounced in the case of the C-series.
- Stress-controlled LCF-tests reveal similar cyclic deformation behavior, but the cyclic hardening and the evolution of mean strains $\varepsilon_M$ is very strongly dependent on the quasi-static mechanical strength of the samples.
- The Manson–Coffin and Basquin approach were used to describe the $S$–$N$-curves obtained from strain and stress-controlled fatigue tests, respectively. A bilinear behavior of plastic deformation was observed, which results from the change of the main deformation mechanism. The fatigue parameters obtained for small applied strain $\varepsilon_A$ and stress $\sigma_A$ amplitudes are in good agreement also with the data reported in the literature. The LCF-parameters for high applied strain $\varepsilon_A$ and stress $\sigma_A$ amplitudes differ, due to the predominant twinning/detwinning cyclic deformation behavior. Literature data are not available for this regime.
- Crack initiation mainly occurred at the specimen surface. The fracture surface shows three different areas. The area of crack propagation increases with decreasing load.

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References