Influence of Hydrothermal Sealing on the High Cycle Fatigue Behavior of the Anodized 6082 Aluminum Alloy

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Abstract: For aluminum alloys, anodizing is a common electrochemical surface treatment to allow for protection against corrosion and wear. The produced conversion layers are first sealed in industrial processes to further enhance the corrosion protection by closing the coating surface pores. In their lifetime, anodized components often undergo cyclic loadings. However, despite the relevance of a sealing treatment, there is a lack of systematic studies regarding its influence on the fatigue behavior of anodized aluminum components. In this work, a 6082-aluminum alloy was anodized in sulphuric acid and the effect of the anodizing treatment with and without further hydrothermal sealing on the fatigue strength was investigated. The thickness and Martens hardness of the coatings were determined and the coating appearance in non-sealed and sealed conditions was analyzed by scanning electron microscopy prior to and after cyclically loading at R = −1. The fatigue strength was significantly decreased by the anodizing treatment, when compared to the bare substrate. However, hydrothermal sealing had a positive influence as the anodized and sealed condition attained a fatigue strength in the range of the bare aluminum. Distinct differences regarding the coating appearances, thickness, and hardness were not observed when comparing the non-sealed and the sealed conditions. After fatigue loading, numerous pronounced radial cracks were present in the anodic coating, but the number of cracks were significantly lower for the hydrothermally sealed coating. Fatigue failure occurred due to propagation of one crack from the coating towards the substrate, resulting in single-point crack initiation, which was similar to the fatigue fracture behavior of the bare aluminum substrate.

Keywords: aluminum alloy 6082; anodic oxide coating; hydrothermal sealing; high cycle fatigue

1. Introduction

Anodization is a widely used electrochemical surface treatment to produce protective conversion coatings against corrosion and wear on high-strength aluminum alloys [1]. Besides the excellent specific mechanical properties of the substrate, such as good strength-to-weight ratio and high fatigue limit, the enhanced corrosion and wear resistance due to the coating enables a broad range of application in the aircraft and automotive sectors [2]. By anodizing aluminum substrates, the surface is transformed into a strongly bonded, porous aluminum oxide coating [3,4]. Besides the influence of the microstructure and chemical composition of the substrate alloy, processing parameters and electrolytes used determine the growth of the coating and the geometry of the cylindrical shaped, cellular-arranged pores [4–6].

Foremost, in the process of aluminum anodization, sealing of the oxide coatings using various coordinated baths and temperatures is conducted to enhance the protection against corrosion by closing the pores [7–11]. In industrial fields, the most common method besides cold impregnation using nickel fluoride [12,13], medium-temperature sealing using dichromate [8,14], and nickel acetate [15,16] is traditional hot-sealing using boiling water [9,17]. Dichromate sealings were used for many years, but are increasingly
replaced due to the toxicity of Cr(VI), which is part of most chromate sealing baths [18]. By hydrothermal sealing in boiling water, the amorphous aluminum oxide is hydrated to crystalline boehmite [8,19], and due to the resulting increase in volume, pores are sealed [9]. Therefore, the general structure of the coating and the hexagonal shape of the pores are not changed [16]. Besides the advantages of non-toxicity, enhanced dielectric properties [10], high elasticity, and uniformity of the coating [20], sealing in boiling water has a high energy consumption and sealing times are long [11]. Furthermore, due to the formation of a boehmite coating, hardness and protection against abrasive wear are decreased [9,10].

As most components undergo cyclical loading in their lifetime, high fatigue resistance is often required, besides protection against corrosion and wear. While anodic coatings fulfill the latter, due to their ceramic and brittle nature, the fatigue strength is decreased [21–25]. Premature failure is promoted by the early initiation of cracks in the porous coatings and, further, by the supported propagation of fatigue-induced cracks due to the good adhesion of the anodic coating on the substrate material [26,27].

Despite the relevance of a sealing treatment for the fields of application of anodized components, there is a lack of systematic studies regarding the influence of a sealing treatment on fatigue behavior. Many studies, which focus on the fatigue behavior of anodized aluminum alloys, use hydrothermal sealed specimens [23,24,27,28] or ones that are sealed in sodium dichromate [21,22] or nickel-acetate solution [29]. As already mentioned above, all referenced studies showed a significant reduction in fatigue strength caused by anodizing and subsequent sealing. However, in all these studies, the fatigue strength of the anodized and sealed alloy was not compared to that of the coated alloy without sealing, so a separation of the effect of the sealing treatment was not provided. To the best of the authors knowledge, only in the study of Priet et al. [30] a systematic comparison was done. They showed that sealing using a trivalent chromium process and conventional hydro-thermal sealing, respectively, contribute further to the loss in fatigue resistance of an anodized 2024 alloy, when compared to the bare aluminum alloy.

To gain further insights into fatigue behavior of sealed anodized aluminum substrates, the aim of the present study is to conduct a systematic investigation of a widely used aluminum alloy, 6082, which is anodized using sulphuric acid followed by conventional hydrothermal sealing. The focus is on the separation of both influencing factors, anodizing and sealing, on the resulting fatigue strength.

### 2. Materials and Methods

#### 2.1. Material

As substrate material, the medium-strength 6082 aluminum alloy (AlSi1MgMn) provided by Bikar-Metalle GmbH (Bad Berleburg, Germany) was used due to its relevance as a structural alloy and its good suitability for the anodic oxidation process (chemical composition is listed in Table 1). The age-hardenable aluminum alloy was solution-annealed at 530 °C for 60 min, quenched in water to room temperature and artificially aged at 170 °C for 65 h to achieve peak strength (refers to condition T6 according to DIN EN 515 [31]). The mechanical properties of the used alloy in this heat-treatment condition are given in Table 2, and the determination of the properties using tensile tests is described in [25]. After heat-treatment, axial specimens with a minimum diameter of 4.0 mm were machined using precision turning (geometry shown in [32]). The surface roughness of the machined fatigue specimens was 0.88 μm Ra maximum.

**Table 1.** Chemical composition of the age-hardenable 6082-aluminum alloy in commercial purity provided by the manufacturer.

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt.%</td>
<td>1.00</td>
<td>0.21</td>
<td>0.05</td>
<td>0.76</td>
<td>0.90</td>
<td>0.02</td>
<td>balance</td>
</tr>
</tbody>
</table>
Table 2. Mechanical properties of the 6082-aluminum alloy in T6 condition determined by tensile testing. The deviation is given in absolute values.

<table>
<thead>
<tr>
<th>Yield Strength in MPa</th>
<th>Ultimate Tensile Strength in MPa</th>
<th>Uniform Elongation in %</th>
<th>Elongation to Failure in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>297 ± 1</td>
<td>307 ± 4</td>
<td>5.2 ± 0.8</td>
<td>23.7 ± 0.9</td>
</tr>
</tbody>
</table>

2.2. Anodizing and Sealing

Prior to the anodizing process, the fatigue specimens were pre-treated. To clean and degrease the surface, ethanol was used. Afterwards, the specimens were etched in 3 vol.% aqueous sodium hydroxide solution (NaOH) at 50 °C for 1 min and pickled in 1:1 nitric acid (HNO₃) at room temperature for 15 s. Between each step, the specimens were rinsed in water.

For the electrolytic anodic oxidation (EAO), 10 vol.% aqueous sulfuric acid (H₂SO₄) was used as an electrolyte, which was constantly stirred with a rod agitator at 200 rpm. The anodizing process was controlled by current density and 540 mA were applied, resulting in 2 A/dm². The temperature was kept constant at 20 °C. The electrochemical treatment was stopped after 40 min, and the specimens were rinsed in water and dried in air.

Additionally, a proportion of the anodized specimens were sealed in deionized water at 98 °C for 60 min. As sealing time is dependent on the thickness and porosity of the anodic coating [9] and in accordance with the requirements of DIN 17611 (3 min for 1 µm thickness) [33], this sealing time was chosen.

2.3. Phase Analysis and Residual Stress Measurements

X-ray diffraction (XRD) technique was used to determine the presence of the boehmite phase after sealing and the residual stresses induced in the aluminum substrate by the anodic coating in non-sealed and sealed conditions. For these measurements, the peak-aged aluminum alloy 6082 was used in the form of 1.5 mm thin sheets to avoid an influence of the geometry of the fatigue specimens on the measuring results. The anodizing and sealing treatment was performed on the sheet material in the exact same manner as for the axial fatigue specimens. The investigations were done using an X-ray diffractometer D8 Advance series 2 (Bruker-AXS, Karlsruhe, Germany) with Bragg Brentano geometry and Co Kα-radiation (40 kV, 40 mA) with a 2 mm pinhole collimator and a Lynxeye XE detector (Bruker-AXS, Karlsruhe, Germany). Line focus under 5° was used for the phase analysis and the identification was based on the PDF2 database of the International Centre for Diffraction Data (ICDD). The residual stress measurements were conducted using point focus and a diffraction angle range between 20° and 130°. The sin²ψ method was applied and the phases used for the determination of residual stresses and their corresponding elastic components are listed in Table 3.

Table 3. Aluminum phase and corresponding elastic components used for the determination of residual stresses.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Diffraction Angle 2θ in °</th>
<th>Crystal Lattice Planes {h k l}</th>
<th>Poisson’s Ratio ν</th>
<th>Young’s Modulus E in MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>94.203</td>
<td>3 1 1</td>
<td>0.35</td>
<td>69,300</td>
</tr>
</tbody>
</table>

2.4. High Cycle Fatigue Testing

To determine the high cycle fatigue behavior, the axial specimens were tested using a resonant testing machine (RUMUL Testronic, Russenberger Prüfmaschinen AG, Neuhausen am Rheinfall, Switzerland). The testing frequency was approximately 100 Hz for the uncoated and anodized specimens. An alternating tension-compression loading (R = −1) was applied, as a previous study showed that this load ratio results in a more pronounced shattering of the coating and is therefore more critical when compared to a tension-tension...
The stopping criteria for the fatigue tests were an endurance limit of $N_D = 10^7$ (specimen is a run-out) or a drop in resonant frequency of 1 Hz or more, which indicates a crack (specimen failed). The fatigue strength was experimentally determined using the pearl chain method in accordance with DIN 50100 [35].

2.5. Microstructural Characterization

For the microstructural characterization of the coating and the analysis of fatigue induced damage, one non-fatigued and each tested specimen of the anodized and anodized and sealed aluminum conditions were cut in longitudinal and cross sections to examine the gauge length. The samples were metallographically polished and vapor deposited with a thin carbon layer before scanning electron microscopic (SEM) analyzes using a LEO 1455VP (LEO Elektronenmikroskopie GmbH, Oberkochen, Germany) and a quadrant backscattering detector (QBSD) to enhance the visualization of irregularities and cracks in the coatings.

On the metallographically polished specimens, coating thickness was determined by optical microscopy using an Olympus GX51 (Olympus Deutschland GmbH, Hamburg, Germany) and 40 measurements on 10 specimens for each condition. The coating hardness was measured for 12 indents on 10 specimens for each condition using the instrumented hardness tester Fischerscope HM 2000XYm (Helmut Fischer GmbH + Co. KG, Sindelfingen, Germany).

In addition to the examination of the metallographically polished specimens, fracture surfaces after fatigue failure were analyzed by digital microscopy using a VHX-500 (Keyence Deutschland GmbH, Neu-Isenburg, Germany). This method allows for the automatic stacking of single images to realize an overall depth of focus for a pronounced surface topography. For this purpose, one specimen each for the bare substrate, the anodized, and the anodized and sealed aluminum was loaded at a stress amplitude resulting in a fatigue life of approximately $10^5$ cycles, which was chosen in accordance with the results of the Woehler tests for each condition.

3. Results

3.1. Coating Characterization

In Figure 1, the X-ray diffractogram of the anodized and sealed aluminum alloy is shown. Hydrothermal sealing led to the formation of crystalline boehmite, which is detectable in the amorphous anodic coating. The aluminum substrate subjacent to the sealed anodic coating is indicated by two pronounced peaks. The general broad appearance of the peak at approximately 45° is a result of different crystalline aluminum phases.

The determined residual stresses for the aluminum substrate in bare and anodized as well as anodized and sealed conditions are listed in Table 4. The bare aluminum substrate is almost free of residual stresses. Due to the anodic oxidation, tensile stresses are induced in the aluminum substrate. Hydrothermal sealing did not influence the amount of residual stresses, as these were almost identical when compared to the anodized non-sealed condition.

<table>
<thead>
<tr>
<th>Coating Condition</th>
<th>Residual Stresses in the Aluminum Substrate in Rolling Direction in MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>bare substrate</td>
<td>1 ± 5</td>
</tr>
<tr>
<td>EAO</td>
<td>15 ± 6</td>
</tr>
<tr>
<td>EAO sealed</td>
<td>16 ± 6</td>
</tr>
</tbody>
</table>

The cross sections of the anodic coatings on the aluminum substrate in both non-sealed and sealed conditions prior to cyclic loading are shown in Figure 2. Both coating conditions exhibit numerous microvoids, which are common for this coating type. During
the early phases of the anodization process, the aluminum-rich matrix of the substrate alloy preferentially dissolves around precipitates, resulting in the decohesion of these [36–38]. Because of dissolved precipitates, pitting-like irregularities are formed. Some precipitates are also incorporated into the coating shown in the micrographs. Furthermore, transverse cracks originating from these microvoids are frequent. At this magnification, distinct differences regarding the coating appearance when comparing the non-sealed and sealed conditions were not visible.

Figure 1. Diffractogram of the anodized and sealed 6082-aluminum alloy. Due to hydrothermal sealing, crystalline boehmite is detectable in the amorphous anodic coating. Identification is based on the PDF2 database of the International Centre for Diffraction Data (ICDD).

Figure 2. SEM micrographs of the anodized 6082-aluminum alloy. Initial coating condition after (a) anodizing and (b) after anodizing and sealing.

Table 5. Coating thickness and Martens hardness of the anodized 6082-aluminum alloy.

<table>
<thead>
<tr>
<th>Coating Condition</th>
<th>Coating Thickness in µm</th>
<th>Martens Hardness in MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Minimum</td>
</tr>
<tr>
<td>EAO</td>
<td>25.9</td>
<td>16.4</td>
</tr>
<tr>
<td>EAO sealed</td>
<td>26.6</td>
<td>19.9</td>
</tr>
</tbody>
</table>

Figure 3. (a) Thickness and (b) Martens hardness of the anodic coating on the 6082 aluminum substrate in unsealed and sealed conditions. The minimum and maximum values are given as deviation.

3.2. High Cycle Fatigue Behavior

The high cycle fatigue behavior of the uncoated, anodized, as well as anodized and sealed aluminum alloy is shown in Figure 4, and the fatigue limits for the three tested conditions are listed in Table 6. The uncoated aluminum substrate exhibits a fatigue...
Thickness and Martens hardness of the unsealed and sealed coating are shown in Figure 3 and listed in Table 5. The average coating thickness for both conditions is approximately 26 µm, whereby the minimum and maximum values are smaller by 37% and larger by 50%, respectively, for the unsealed coating (see Figure 3a). However, the deviation of the coating thickness is slightly smaller for the sealed coating. The Martens hardness of the unsealed anodic oxide coating is approximately 2800 MPa. After sealing the coating exhibits a slightly higher hardness by approximately 3%, when compared to the unsealed condition, but the deviation in hardness is similar for both coating conditions (see Figure 3b).

![Figure 3](image_url)

**Figure 3.** (a) Thickness and (b) Martens hardness of the anodic coating on the 6082 aluminum substrate in unsealed and sealed conditions. The minimum and maximum values are given as deviation.

<table>
<thead>
<tr>
<th>Coating Condition</th>
<th>Coating Thickness in µm</th>
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<tr>
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</tr>
</tbody>
</table>

### 3.2. High Cycle Fatigue Behavior

The high cycle fatigue behavior of the uncoated, anodized, as well as anodized and sealed aluminum alloy is shown in Figure 4, and the fatigue limits for the three tested conditions are listed in Table 6. The uncoated aluminum substrate exhibits a fatigue strength of 125 MPa and by anodic oxidation the fatigue strength is significantly decreased by approximately a third to 85 MPa. However, sealing after anodizing leads to an enhanced fatigue resistance and a fatigue strength equal to the uncoated substrate. As indicated by the single measured points, the progression of fatigue limits for the applied stress amplitudes is similar for the three tested conditions, and the progression of the anodized condition is almost shifted parallel to lower stress amplitudes. For both coated conditions, unsealed and sealed, a higher deviation of the fatigue strength, particularly for lower stress amplitudes, is noticeable, which is expressed in a more horizontal progression of the fatigue strength near the fatigue limit of $10^7$ cycles.
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Figure 4. High cycle fatigue behavior of the 6082-aluminum alloy in T6 condition, uncoated and anodized. Anodizing reduces the fatigue strength significantly, but with subsequent sealing, the fatigue strength of the uncoated peak-aged substrate can be nearly maintained.

Table 6. Fatigue limit at $N_D = 10^7$ cycles under symmetrical tension-compression loading (load ratio $R = -1$) of the uncoated and anodized 6082 aluminum alloy in T6 condition.

<table>
<thead>
<tr>
<th>Al 6082 T6</th>
<th>Stress Amplitude $\sigma_a$ in MPa</th>
<th>Percentage Change in Fatigue Limit, When Referring to the Uncoated Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncoated substrate</td>
<td>125</td>
<td>-</td>
</tr>
<tr>
<td>EAO</td>
<td>85</td>
<td>$-32%$</td>
</tr>
<tr>
<td>EAO sealed</td>
<td>130</td>
<td>$+4%$</td>
</tr>
</tbody>
</table>

3.3. Coating Characterization after Fatigue Loading

Cyclic loading leads to fatigue-induced damage in the form of radial, split-like cracks in the anodic coating (see Figure 5a,c). The crack path is not influenced by the appearance of incorporated precipitates or transverse cracks and they are resting at the interface with the aluminum substrate (see Figure 5b,d). Mostly, these cracks are spaced somewhat periodically throughout the coating cross-section. A distinct difference in the characteristics of these fatigue-induced cracks was not observed when comparing both coating types. However, a systematic investigation of the gauge length showed a significantly lower number of these radial cracks present in the sealed coating when compared to the unsealed condition.

Fatigue-induced failure is mostly caused by the disproportionate growth of one critical crack in the unsealed anodic coating, which propagates from the resting point at the interface towards the aluminum substrate (see Figure 6). After reaching the stopping criterion for the fatigue test of a drop of 1 Hz in resonant frequency, the crack causing fatigue failure exhibited a length of more than 2 mm in the substrate. Although no similar crack could be observed for the sealed coating, it is assumed fatigue failure was caused in the same manner independent of the additional sealing treatment. Further, it has to be noted that the examined cross section and therefore the occurrence of cracks and their detectability are dependent on the metallographically prepared plane as it is only a two-dimensional depiction.
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Figure 6. SEM micrographs of the anodized unsealed 6082 aluminum alloy after fatigue failure. (a) the specimen failed due to a crack propagating from the coating into the aluminum substrate. (b) radial crack in the coating as a starting point for failure (section marked in (a) with a white rectangle).

3.4. Fatigue Fracture

Investigation of the fracture surfaces after fatigue failure showed single-point crack initiation for all tested conditions (see Figure 7, zone marked with a white ellipse). Distinct differences between the bare substrate, the anodized, and the anodized and sealed aluminum regarding the appearance of the fracture surface were not noticeable. Although both anodized conditions exhibited many radial cracks in the coating stopping at the interface (see Figure 5), only one crack was able to grow from the interface further into the aluminum
substrate and cause fatigue failure. This observation is in accordance with the results of the microscopic examination of the metallographically polished specimens.

![Figure 7](image-url) Digital micrographs of the fracture surfaces of the 6082-aluminum alloy after fatigue failure. (a) bare substrate, (b) anodized and (c) anodized and sealed. Crack initiation started at one point for all three conditions (marked with white ellipse).

4. Discussion

4.1. Coating Characterization

The formation of the cellular pores during the anodization process leads to tensile residual stresses in the pore ground and in the interface [39,40], further resulting in tensile residual stresses in the aluminum substrate [22,41], which is in line with the results of the
investigated anodized condition. Hydrothermal sealing did not influence the presence of these anodizing induced tensile stresses in the aluminum substrate. As far as our knowledge goes, there are no other studies reporting measurements of residual stresses in the substrate after sealing treatment, which would enable a distinct evaluation of our own results. However, it cannot be concluded with certainty, whether or not the formation of boehmite led to a change in residual stress state over the coating cross section, as the crystalline peak indicating boehmite in the XRD diffractogram was too small to be used for residual stress measurements. Regarding the determination of residual stresses in the coating, Goueffon et al. [42] used the curvature method, and they observed compressive residual stresses in colored anodic coatings after sealing in nickel acetate and boric acid.

Overall, the general coating appearance was not influenced by the hydrothermal sealing treatment, and the transformation of aluminum oxide to boehmite did not affect the presence of the characteristic microvoids in the coating. In contrast to studies by Shazhad et al. [29] and Goueffon et al. [42], sealing did not cause radial cracks in the coating. The appearance of cracks might be a result of the used sealing treatment and the additives in the sealing bath, as in both studies the coatings were sealed in an aqueous solution with nickel acetate. As expected, hydrothermal sealing did not influence the coating thickness. However, the greater flatness and uniformity of hydrothermal sealed anodic coatings [20] might explain the slightly smaller deviation of the thickness of the sealed coating when compared to the non-sealed condition. An increase in coating hardness after hydrothermal sealing was also observed by Wan et al. [43], but the authors did not provide a possible explanation for this effect. However, these results are in contrast to the common knowledge that hydrothermal sealing decreases the coating hardness due to the transformation of harder aluminum oxide into softer boehmite [10,44]. Therefore the slight hardness increase in our case cannot be explained.

4.2. High Cycle Fatigue and Fracture Behavior

According to literature [21–24,45], anodizing leads to a significant reduction in fatigue strength when compared to the bare aluminum substrate. The anodic coating itself is the fatigue life-limiting factor as cracks can readily form under cyclic loading due to the brittle ceramic character of the coating, which is clearly demonstrated in the SEM micrographs. Consistent to an own previous study [25], the numerous fatigue-induced radial cracks stop at the interface to the substrate material, and failure occurs as a result of the growth of one or more cracks that can propagate towards the substrate. The propagation of cracks is further promoted by the tensile residual stresses in the substrate induced by the anodic coating [41].

In contrast to the study of Priet et al. [30], sealing treatment after anodization does not contribute to a further loss in fatigue strength. Instead, hydrothermal sealing results in an enhancement of fatigue strength and the fatigue limit of the bare aluminum substrate is attained. This observation is also in contrast to the studies using anodized and hydrothermally sealed specimens solely for their investigations [23,24,27,28], which show a decreased fatigue resistance after anodizing and sealing. One possible explanation for the different fatigue performance could be the investigated coating thickness. For the studies by Priet et al. [30], Shazhad et al. [29], and Domingues et al. [28], much thinner coatings with a thickness of approximately 2–6 mm were used, when compared to the previously investigated coatings with quadrupled thickness. Furthermore, the hydrothermal sealing time could also be an important influencing factor, as the studies from Cirik et al. [23] and Genel et al. [24] used similar coating thicknesses, when compared to our study, but the sealing time was significantly shorter with 4 min per specimen in their work. This is also the case for the study by Hemmouche et al. [27], which investigated thinner coatings in the range of 6–14 µm sealed for half an hour when compared to the sealing time of 60 min used in this study. As aluminum oxide is transformed to boehmite during sealing, a longer sealing time and a higher coating thickness could have led to a higher content of boehmite in general. Due to the crystalline boehmite, the tendency to brittle ceramic
fracture is significantly decreased when compared to the anodic coating before sealing, which is in line with the results of the microscopic analysis showing a significantly lower number of radial cracks for the sealed coating.

Many studies [23,29,30] have reported multi-site crack initiation under fatigue loading for anodized as well as anodized and sealed coatings. However, this was not observed in our study. After fatigue loading, even though many radial cracks were present in the coating stopping at the interface, only one crack had grown further towards the substrate, leading to failure for the non-sealed as well as the sealed anodized condition. Pits resulting from etching and pickling pre-treatment before anodizing are often described as the reason for multiple crack initiation sites during fatigue loading [26,45,46]. Savas et al. [47] showed that etching and pickling times in the range of 120 s and 60 s, respectively, are significantly less destructive to the surface when compared to longer pre-treatment times. For our study, the same pre-treatment solutions were used, but the exposure times were only about a third as high as those used by Savas et al. [47]. Therefore, we assume that our pre-treatment routine did not cause adversely affected pits in the substrate surface and, as a result, for both anodized conditions, failure due to single-point crack initiation was promoted similarly to the bare aluminum substrate.

The results of this study clearly demonstrate the necessity for further systematic investigations regarding the influence of a sealing treatment on the fatigue behavior of anodized components. To clearly understand the underlying mechanism for fatigue failure and fracture of hydrothermal sealed anodic coatings, it is crucial to systematically compare different sealing times and different anodic coating thicknesses. To separate the influence the sealing treatment has on the comparison between the bare substrate and the anodized alloy is mandatory. Further, to evaluate the tribological properties of the hydrothermal sealed coating and therefore the suitability for the intended application, wear and corrosion tests have to be done in addition to the fatigue test.

5. Conclusions

The influence of hydrothermal sealing on the high cycle fatigue behavior of an anodized 6082-aluminum alloy was investigated in this study. The generated coatings were analyzed using scanning electron microscopy and thickness and hardness were determined prior to and after sealing. The fatigue strength was compared for the peak-aged bare substrate alloy and at room temperature anodized non-sealed and sealed alloy, respectively. Conclusions can be drawn as follows:

1. By anodizing the fatigue strength is decreased by approximately a third, when compared to the fatigue strength of the peak-aged bare aluminum substrate;
2. Hydrothermal sealing after anodizing significantly improves the fatigue resistance, when compared to the non-sealed anodized condition, and the fatigue strength of the bare aluminum substrate is attained;
3. Coating thickness and Martens hardness as well as the coating appearance generally are not influenced by hydrothermal sealing;
4. After fatigue loading many radial cracks were present in the anodic coating stopping at the interface. However, the number of cracks was smaller for the hydrothermally sealed condition. Fatigue failure occurred due to single-point crack initiation for the bare substrate as well as for the anodized and the anodized and sealed condition, where one crack has grown further from the coating towards the substrate.

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Conflicts of Interest: The authors declare no conflict of interest.

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