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Influence of corrosion on the mechanical properties of hybrid sandwich structures with CFRP face sheets and aluminum foam core

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A B S T R A C T

Hybrid materials, such as sandwich structures consisting of an aluminum foam core and CFRP face sheets, offer high lightweight design potential. However, conductive pairing of two materials with different electrochemical potential bears the risk of galvanic corrosion inside an electrolytic environment. Due to the nature of the manufacturing process, the sandwich structures investigated within this contribution are susceptible to corrosion. Multiple specimen variants with differing foam core layers were exposed to a salt spray environment for up to 240 h. These corroded specimens were mechanically characterized using the flatwise tension test. Their mechanical properties were compared to reference specimens without corrosion. It was found that both open and closed cell sandwich specimens showed significant reductions in both strength and stiffness. Comparisons to alternative sandwich specimens consisting of a Nomex honeycomb core and CFRP face sheets, which underwent the same corrosion procedure, seem to prove that the mechanical degradation was indeed a result of corrosion, as the Nomex specimens did only show a significantly smaller decrease in strength, which probably resulted from material scatter superposed with water absorption. The erosion of the metallic core layer should be quantifiable by the determination of mass reduction. Therefore, a chemical cleaning procedure in order to remove any corrosion products from the specimen surface was applied. However, the procedure either led to a further mass decrease by chemical removal of the aluminum structure, or to mass increase by a chemical reaction of the detergent with the face sheets. Thus, complementary X-ray measurements by μ-CT were carried out. Specimens were scanned before and after corrosion, the respective volumetric densities were compared in order to verify material erosion. However, no significant change in volumetric density could be observed.

1. Introduction

Modern lightweight applications benefit from innovative hybrid materials which offer great mechanical properties such as high stiffness or strength in combination with a low density [1,2]. Sandwich materials, consisting of a lightweight core layer as well as dense face sheets, are prominently used in aircraft and aerospace [3–5], as well as wind turbines [6] or marine applications [7,8]. They offer great specific flexural stiffness, good impact properties as well as good thermal and acoustic insulation [9–11]. There is a large variety of possible sandwich architectures and material combinations. Among others, Nomex honeycomb structures [4,12] as well as metallic foams [13] are often used as core layers. For the sandwich faces, metallic sheets [13–15] or fiber reinforced plastics (FRP) [16] can be applied. Commonly, the connection between the different sandwich layers is achieved via a thin adhesive interlayer [17]. Alternatively, a metallic bond may be used, e.g. when pairing a foamed aluminum core with aluminum face sheets [13].

In [18] a novel method for producing hybrid sandwich panels was applied by the authors of this contribution. A single step polyurethane (PUR) spraying process was used to simultaneously create the face sheet material as well as the interface between the CFRP face sheets and the metallic aluminum foam core layer by foaming of the PUR. Varying types of core materials can be used to create sandwich structures, ranging from different metallic foam core types to non-metallic ones, such as Nomex-honeycomb core material.

Due to the nature of this process, it is possible that some fibers stayed in direct contact with the aluminum core, as the fibers were placed directly on the core before the application of PUR resin. It could also be possible that some carbon fibers were not completely wetted with resin, creating a conductive carbon fiber surface. Therefore, a conductive contact of carbon fibers to the aluminum foam is possible. Carbon fibers own a relatively high, positive electrochemical potential [19]. Aluminum on the other hand has a very low negative electrochemical potential. When these two materials are conductively bonded inside an electrolytic environment, their difference in potential leads to a large driving force for electrochemical corrosion processes, enabling

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galvanic corrosion. Whenever the risk of conductive coupling between these two materials emerges, galvanic corrosion phenomena have to be taken into account. Wang et al. investigated the corrosion properties of CARALL, a hybrid laminate consisting of layers of CFRP and aluminum sheets [20]. It was found that galvanic corrosion processes may lead to delamination at the CFRP metal interface due to insufficient insulation. Similar work was conducted in [21] by Mandel et al. for hybrid riveted joints between CFRP and aluminum sheets. The interface area of these hybrid specimens showed significant corrosion damage after salt spray testing. Further investigations into this subject can be found in [15,22,23].

Within the aforementioned investigations it is commonly stated that, during the corrosion process, the anodic partial reaction usually takes place on the metallic component, e.g. aluminum, while the cathodic partial reaction takes place on the carbon fibers. These reactions lead to an electrical current from the anode to the cathode flowing through the conductive contact between the two materials. Simultaneously, an ion current from the anode to the cathode flows through the electrolyte. This process leads to the corrosive degradation of the anodic material as well as the precipitation of corrosion product on the cathode [21,24]. In [25] it was stated that, in the case of aluminum, the predominantly formed corrosion product typically is bayerite ($Al(OH)_3$) or, at higher corrosion temperatures, boehmite ($AlO(OH)$).

While the appearance of galvanic corrosion phenomena is thoroughly researched for a wide variety of hybrid materials, only little investigation into the effects of galvanic corrosion on the mechanical properties of said materials can be found in open literature, especially for hybrid sandwich structures. In many areas of application however, these materials are exposed to a corrosive environments for extended periods of time. Possible mechanical degradation of hybrid structures due to corrosive damage may therefore significantly reduce their lifespan. However, for hybrid sandwich materials in particular only little preliminary research was conducted. In [15], Fischer et al. examined the influence of corrosion on the mechanical properties of a sandwich assembly made out of an aluminum honeycomb core which was adhesively bonded to CFRP face sheets. These specimens underwent accelerated corrosion followed by mechanical testing. For this purpose, the flatwise tension test was used. It was found that the tensile strength of corroded sandwich specimens was reduced by 41% after two weeks of exposure to the corrosive environment. It was assumed that corrosive damaging of the aluminum adhesive interface was responsible for this loss of strength.

In [7], a closed cell aluminum foam was examined after 1000 h of salt spray testing. Although no mechanical characterization of those corroded sandwich specimens was carried out, the results of this study showed a large amount of corrosion product inside the specimen foam cells. These results show that the aluminum foam used in this work may also be susceptible to corrosion.

The aim of this study was to characterize the influence of corrosion on the mechanical properties of hybrid sandwich materials. Two different base types of sandwich specimens with aluminum foam core layer were examined (open and closed cell) with one additional closed cell core variant which was sand blasted, as well as a sandwich type with a Nomex honeycomb core for reference. Before mechanical testing, specimens had to undergo an accelerated corrosion process for three different levels of time (48 h, 96 h and 240 h). For this purpose, the neutral salt spray test (NSS) was used.

Initially, it was intended to characterize the corroded sandwich specimens using the DCB (Double Cantilever Beam) testing procedure according to ASTM D5528-13 to determine the interlaminar fracture toughness G_{IC}. However, an uneven crack propagation as well as crack kinking into the core layer lead to a large scatter of measured data for both corroded and reference sandwich specimens, rendering the DCB testing method unsuitable for aluminum foam core sandwiches. Instead, the flatwise tension test according to DIN 53 292 was used for mechanical testing. A damaging of the foam core or the core-face sheet interface due to corrosion should lead to a reduction of the tensile properties of the sandwich specimens. Also, previous work by Fischer et al. demonstrated that this testing procedure can be successfully used to determine the influence of corrosion on the tensile strength of sandwich specimens [15].

Tensile strength and Young's Modulus of both corroded and reference specimens have been determined. The mechanical properties of specimens of different corrosion duration and varying core types have been compared to determine the progression of the corrosion process and to point out the influence of the core type. Sandwiches with a Nomex honeycomb core layer were also corroded and mechanically tested. As no galvanic coupling appears within this sandwich assembly, no corrosion damage was to be expected. By comparing the results of the Nomex honeycomb sandwich specimens with the results of the aluminum foam core sandwich specimens, conclusions concerning the source of a possible loss of mechanical properties could be drawn. In addition to the mechanical testing procedures, a determination of mass loss was conducted to verify corrosion damage of the sandwich specimens. To this end, both a chemical cleaning procedure with multiple cleaning cycles and measurements by X-ray computed micro-tomography (μCT) were conducted. A relation between the loss of tensile strength and Young's Modulus as well as loss of mass has been pointed out.

2. Materials

Two different hybrid sandwich panels with varying aluminum foam core materials where provided for the present work (Fig. 1). The first core material was an open cell aluminum foam (AlSi7Mg0.3, 10 ppi, approx. 5% relative density) produced by the company m-pore in Lindenberg, Germany. The second aluminum foam core type used was a closed cell aluminum foam named Alcoras (4 ppi, approx. 8% relative density) which was supplied by AlCarbon, a company set in Bremen, Germany.

The closed cell aluminum foam was additionally used in a sand-blasted condition. By sand-blasting, horizontal cell walls were removed, creating a lighter aluminum foam structure, somewhat resembling a honeycomb structure. The mechanical properties were assumed to be only slightly weaker, as the horizontal cell walls carry less transverse and shear load as the vertical cell walls. However, some vertical cell walls were also removed by the blasting process, especially close to the

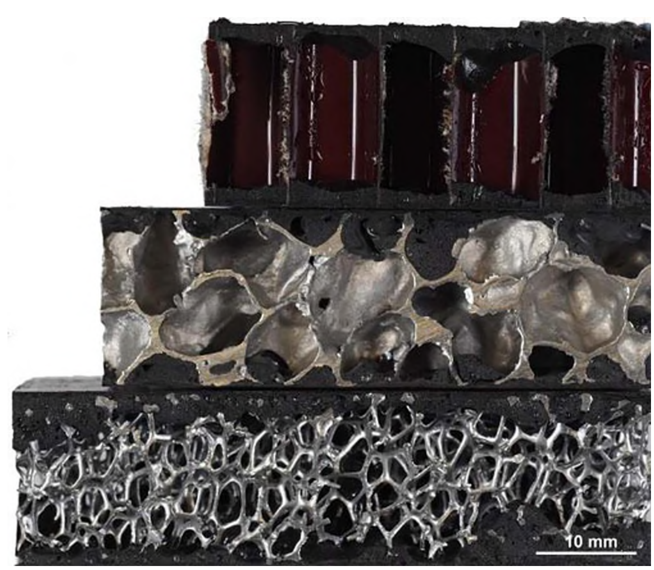


Fig. 1. Sandwich specimens with Nomex honeycomb core (top), closed cell (middle) and open cell aluminum foam core (bottom).

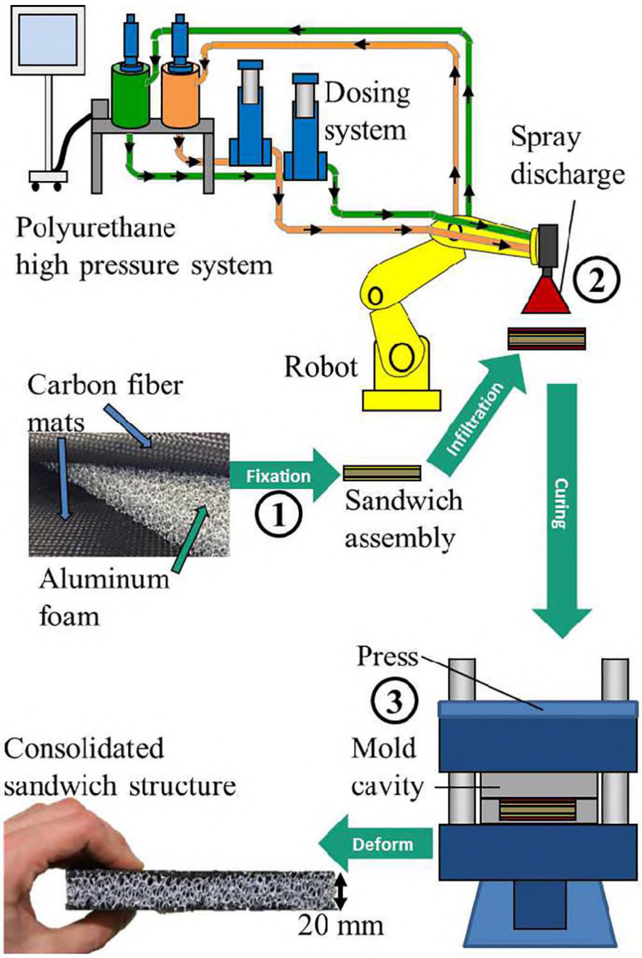


Fig. 2. direct PUR spraying process [18].

surface. The blasted foam cores thus bear a significantly lower contact volume to the face sheets. As the potential of corrosion still exists, the specimens with blasted aluminum foam cores were nonetheless included in the tests.

In addition to the sandwich panels with metallic core material, hybrid sandwiches with a Nomex honeycomb (ECA9.6–48) core layer where investigated as a reference. This core material was manufactured by Eurocomposites in Echternach, Luxembourg. As described in the previous section, sandwich specimens with the latter core layer do not contain materials of different electrochemical potential; therefore no corrosion damage should occur.

The face sheets of the sandwich panels where manufactured using a modified PUR spraying process as shown in Fig. 2. Woven or NCF carbon fiber fabrics, provided by Lange + Ritter in Gerlingen, Germany, were loosely placed upon the core material. A robot arm was used to spray PUR, consisting of the isocyanate PUR 900 and the polyol PUR 569 IT (both provided by Rühl Polymer GmbH, Friedrichshof, Germany), into the mold cavity to avoid fiber misalignment due to the handling of a wet sandwich assembly. The sandwich assembly was placed into the mold directly following the described PUR application. The upper PUR layer was then applied directly onto the upper panel face area. The sandwich panel was cured inside the closed mold cavity for 10 min at 60 °C. During this curing process, the PUR foamed and infiltrated the core layer, creating an interface between face sheets and core material while also serving as the matrix for the face sheets. This manufacturing process of sandwich panels allows for an increased connection surface between core and face sheets compared to commonly used adhesively bonded sandwich panels [18]. In case of an incomplete wetting of the fiber layer through the PUR foam a conductive link between the metallic core layer and the carbon fibers may be created, possibly leading to galvanic corrosion.

3. Experimental

3.1. Corrosion chamber

An accelerated corrosion process of sandwich specimens was achieved by means of a neutral salt spray test (NSS) as described in DIN EN ISO 9227. Sandwich specimens were placed inside a climate chamber where a nozzle was used to continuously spray a 5% NaCl-solution, creating a corrosive environment. Spraying pressure was set to 1.0 bar throughout the whole experimental procedure. A heating bath was used to regulate climate chamber temperature which was set to 35 °C. Sandwich specimens were exposed to the corrosive environment for three levels of time (48 h, 96 h, 240 h), after which they were removed from the chamber, cleaned with clear water and prepared for the following mechanical testing procedures.

3.2. Flatwise tension test

Mechanical testing of sandwich specimens was carried out using the flatwise tension test according to DIN 53 292 at standard room temperature. Sandwich specimens with a square base area (50 mm side length, 20 mm thickness) were mounted in a ZwickRoell ZMART.Pro universal testing machine with a maximum tensile force of 100 kN using adhesively bonded loading blocks for force transmission (Fig. 3).

Testing speed was set to 0.5 mm/min. The Young's modulus was measured using an un- and reloading cycle which was initiated after reaching a force of 1000 N. For the aluminum foam core sandwich variants, a minimum of four specimens per corrosion duration level were investigated, while for the Nomex honeycomb core variants, only

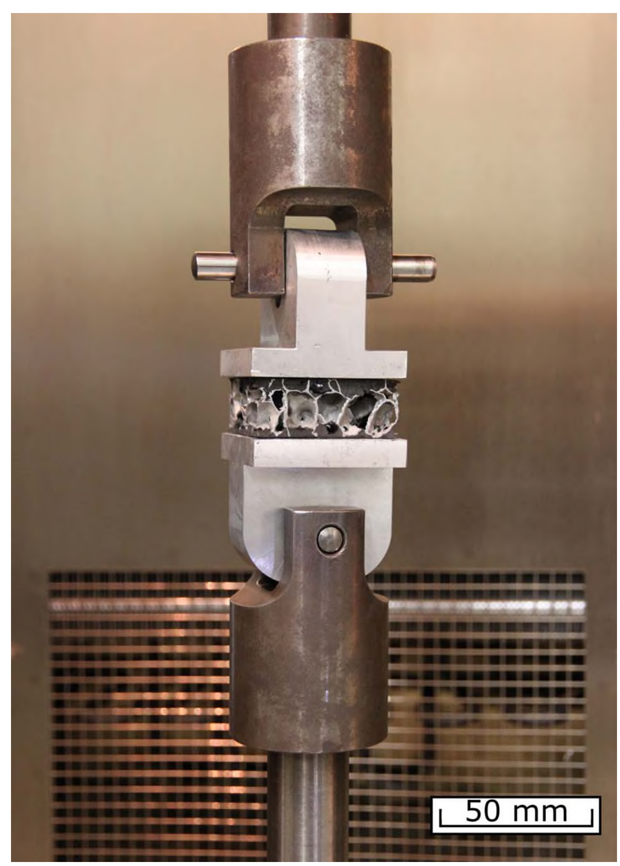


Fig. 3. flatwise tension test assembly.

the maximum corrosion duration level was investigated as no corrosion was to be expected.

3.3. Determination of mass loss of corroded sandwich specimens

In order to detect possible corrosion damage of sandwich specimens after exposure to the salt spray environment, a determination of mass loss was conducted following DIN EN ISO 8407:2014. Three additional sandwich specimens (75 mm length, 25 mm width, 20 mm thickness) per core type were corroded for 96 h each. These corroded specimens were submerged in nitric acid ($HNO3$, = 1.42 g/ml) for two minutes using an ultrasonic bath to assist the cleaning process. Afterwards, the mass of the cleaned specimen was measured. This cleaning cycle was repeated until a total number of four cycles per specimen was reached. Using a linear extra-polation method, the specimen mass without corrosion product could be calculated. By comparing this mass with the specimen mass before salt spray testing, the mass loss of the sandwich specimens could be determined.

3.4. Measurements by X-ray computed micro-tomography (μCT)

As an additional method for the determination of corrosion damage, measurements by X-ray computed micro-tomography (μCT) were carried out on specimens before and after the corrosion process. An Yxlon Y.CT Precision μCT-System was used. The tube and reconstruction parameters were the same for each measurement: The tube was operated at 180 kV and a current of 0.4 mA, with a 0.5 mm copper filter. 2700 projections at 500 ms integration time were reconstructed.

The reconstructed image data was evaluated with Fiji [26]. The scanned images of each specimen before and after the corrosion process were cut to show the same section. The face sheets were excluded from the images, as only the aluminum foam was investigated. For binarization, two methods were used: The default setup used in Fiji, and a manually fixed threshold. The manually fixed threshold was set by comparing the relative mass density of the aluminum foams to the volumetric density of the scanned specimens before the corrosion process. If a fraction of the aluminum foam was eroded during the corrosion process, a difference in volumetric density should be observed using the described method.

4. Results & discussion

4.1. Visual inspection of corroded sandwich specimens

Following the exposition of the sandwich specimens to the salt spray environment, these specimens underwent a visual inspection before further mechanical testing was performed. Fig. 4 shows that all sandwich types with aluminum foam core exhibited a significant amount of corrosion products inside the respective core material, including the specimens with a blasted core layer.

The corrosion products show a visual similarity to corrosion products detected by [7] in aluminum foam. Especially closed cell foams showed a large amount of corrosion products inside cells close to the foam surface. The amount of corrosion products grew with increasing corrosion duration for both core types. The large quantity of corrosion product suggests that corrosion processes occurred during salt spray testing, however, no corrosion damage of any kind, e.g. pitting corrosion, in either core type could be found. Sandwich specimens with Nomex honeycomb core on the other hand showed no signs of corrosion damage or corrosion products at all, even after 240 h of corrosion time.

4.2. Mass loss

Table 1 shows the results of the mass loss determination using chemical cleaning procedures for all sandwich types. m_R describes the mass of the specimen before it was corroded. m_0 describes the mass after corrosion and before the first cleaning cycle, whereas m_1 describes the mass after the first cleaning cycle took place. All but one of the specimens showed an increase in mass after the first cleaning cycle.

For the blasted cell core specimens, the mass was determined for all tested specimens, before corrosion and after the ultrasound cleaning procedure. Table 1 shows the average mass for each increment of corrosion exposure time. The results are in agreement with the observations for the open- and closed cell foams: All specimens show a slightly increased mass after the corrosion process.

Fig. 5 shows that the cleaning procedure lead to a successful

Fig. 4. Sandwich specimens with open (top) and closed cell aluminum core layer (bottom) directly after 240 h of exposure to the corrosive environment.

Table 1
Chemical determination of mass loss of corroded specimens.

Core type	No.	m_R (g)	m_0 (g)	m_1 (g)
	1	8.288	8.324	8.319
Open cell	2	9.660	9.678	9.696
	3	8.663	8.692	8.697
	1	11.952	12.002	12.054
Closed cell	2	11.539	11.606	11.990
	3	12.034	12.111	12.336
	(48 h)	12.49	-	12.57
Blasted	(96 h)	12.54	-	12.64
	(240 h)	12.23	-	12.49

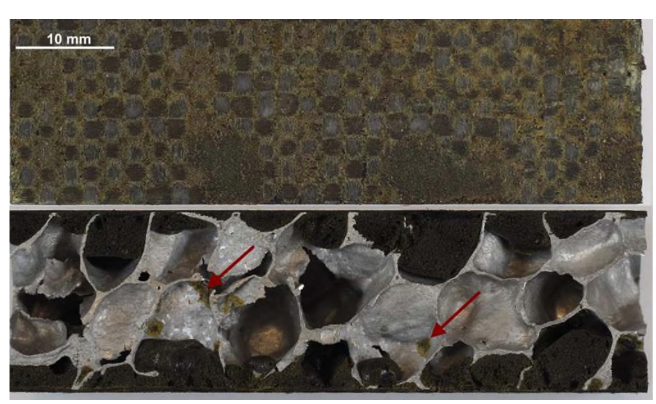


Fig. 5. Corroded sandwich specimen with aluminum foam core after the first cycle of the chemical cleaning procedure, face sheet (top) and core layer (bottom).

removal of corrosion products inside the sandwich sample, however, the detergent also damaged parts of the aluminum foam structure. In addition, a yellowish discoloration of the sandwich face sheets resulted from the cleaning procedure. This discoloration indicates a possible chemical reaction between the face sheet material and the detergent leading to the formation of reaction product as well as an increase of specimen mass.

4.3. Density measurements by X-ray computed microtomography (μCT)

The relative mass density of the aluminum foams inspected by μCT was 8.3 %. The manually fixed threshold was set to a grey value of 200 (16 bit greyscale image), resulting in an average volumetric density of 8.47 %, approximately resembling the mass density. The volumetric density determined by the default threshold was 7.34 %.

Throughout all tested specimens, regardless of the time of exposure inside the corrosion chamber, and valid for both thresholding methods, the change in volumetric density was less than 1 %.

This agrees with the observations for the determination of mass loss, where no relevant mass loss could be observed. It can thus be concluded that the applied thresholding method and the evaluation of volumetric density is suitable, but the corrosion damage is not visible as an erosion of the core.

4.4. Flatwise tension test

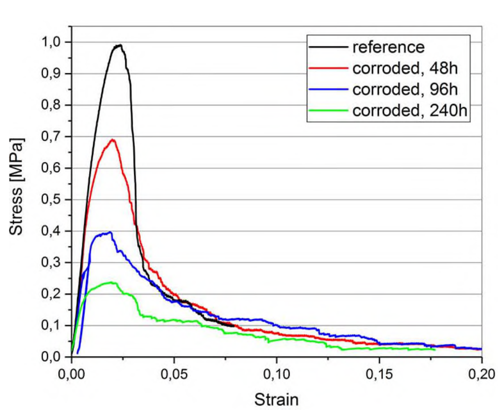
The stress–strain-curves of the open cell sandwich specimens resulting from flatwise tension tests are shown in Fig. 6(a). One stress curve for each given corrosion duration is plotted, as is the stress curve of a non-corroded specimen for reference. After only 48 h of exposure to the corrosive environment, specimens already showed a distinct decrease of tensile strength. With each following step of increasing corrosion duration, a further reduction in tensile strength was noticed.

All tested open cell sandwich specimens exhibited failure inside the aluminum foam core layer independent of corrosion duration. The crack was usually initiated at the center core area, followed by uneven crack propagation through the core layer. The mean tensile strengths of the open cell sandwich specimens as a function of the corrosion duration are given in Fig. 7(a). As this graph shows, the reference specimens reached the highest average tensile strength of 0.94 MPa. Sandwich specimens, which were corroded for 48 h, exhibited a decrease in mean tensile strength to 75% (0.70 MPa) of the original tensile strength. After 96 h and 240 h of corrosion duration the average tensile strength was determined to be 41 % (0.39 MPa) respectively 24% (0.23 MPa) of the tensile strength previous to the corrosion process. Similar results can be found for the average stiffness of the open cell sandwich specimens, which was normalized to the mean stiffness of the reference specimens, as can be seen in Fig. 7(b). After 48 h of corrosive exposure, no significant decrease in mean stiffness could be seen in comparison to the reference specimens. Further increases in corrosion duration however lead to a decline in mean stiffness to 77% after 96 h respectively to 54% after 240 h.

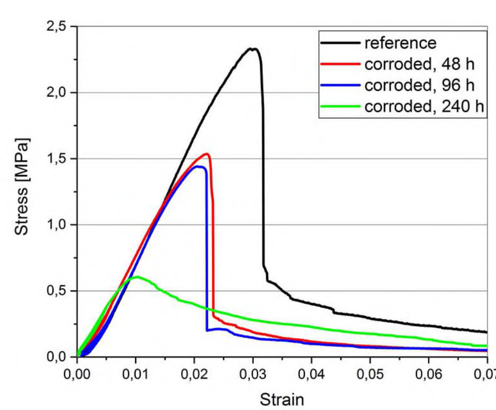
Fig. 6(b) shows the stress–strain-curves of the sandwich specimens with a closed cell aluminum foam core structure for the respective corrosion durations. As already observed for the sandwich specimens with open cell core structure, the highest tensile strength was once again obtained with the reference specimens. Reduced tensile strengths were achieved with increasing corrosion duration. Also, a change in failure mode was detected with increasing corrosion duration (Fig. 8). While all but one of the five reference specimens failed at the interface between core and face sheet, a shift towards core failure was noticed with increasing corrosion duration. Specimens, which were exposed to the corrosive environment for 48 h respectively 96 h, exhibited core failure in two out of five cases, whereas 240 h of salt spray testing resulted in all four of the specimens failing inside the core layer during flatwise tension testing. Failure at the interface between core and face sheet always resulted in a sudden drop in the respective stress curve whereas core failure lead to a rather even decrease of measured stress during further crack propagation (Fig. 9). In addition, it was noted that specimens failing at the interface always reached higher maximum stress levels than specimens of equal corrosion duration failing inside the core layer.

A comparison of mean tensile strengths of corroded closed cell sandwich specimens as function of the corrosion time is shown in Fig. 7(c). Reference specimens reached the highest average tensile strength (1.96 MPa), whereas corrosion durations of 48 h respectively 96 h resulted in a reduction of mean tensile strength to 64% (1.25 MPa) respectively 57% (1.11 MPa) compared to the reference. After 240 h of exposure to the corrosive environment, the average tensile strength was determined to be 30% (0.58 MPa). Corroded specimens showed a mean stiffness which was reduced to approx. 90% after 48 h and 96 h respectively 79% after 240 h compared to the reference specimens (Fig. 7(d)).

As previously described, the sandwich specimens with a sandblasted closed cell foam core also showed large amounts of corrosion product inside their core layers after exposure to the corrosive environment. Therefore, a similar degradation of the mechanical properties of the sandwich specimens was to be expected with increasing corrosion duration. However, as Fig. 7(e) shows for the mean tensile strength of blasted core specimens, this reduction was neither as pronounced nor as consistent as with the two previously discussed specimen variants. The reference specimens reached the highest mean tensile strength (0.77 MPa), while the corroded specimens reached 0.70 MPa and 0.44 MPa after 48 and 96 h, respectively. The last set of specimens,

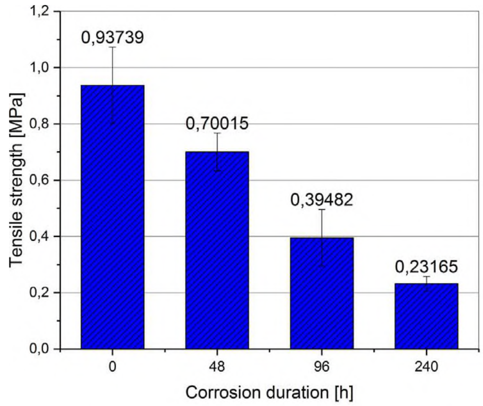


(a) open cell

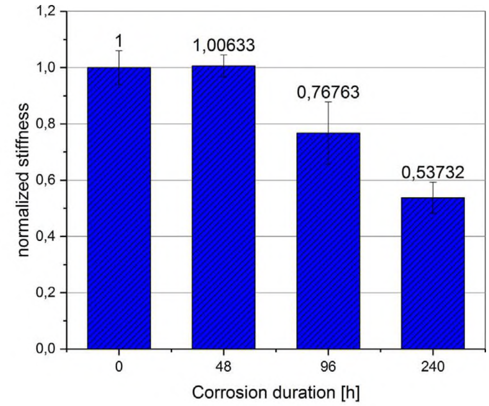


(b) closed cell

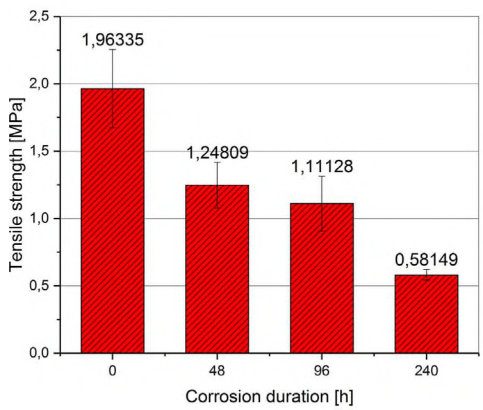
Fig. 6. Stress-strain curves of open cell (a) and closed cell (b) hybrid sandwich specimens during the flatwise tension test.



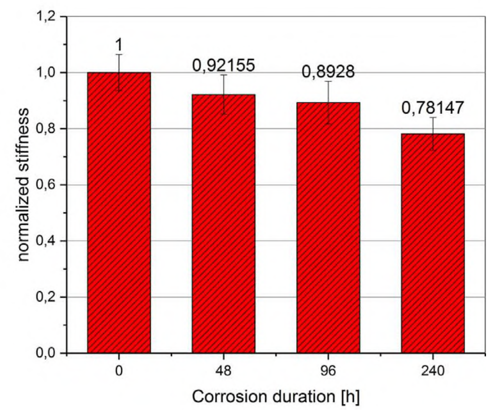
(a) open cell mean tensile strength



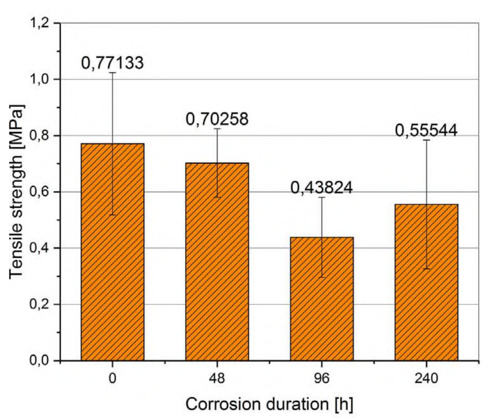
(b) open cell normalized mean stiffness



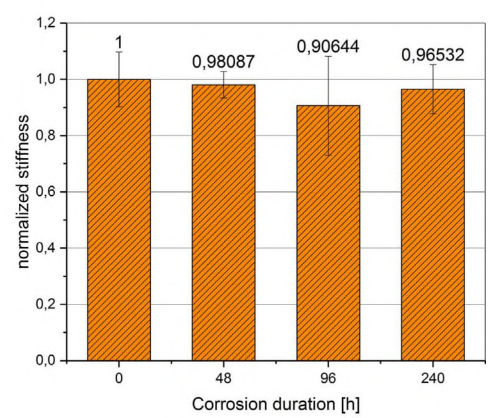
(c) closed cell mean tensile strength



(d) closed cell normalized mean stiffness



(e) blasted mean tensile strength



(f) blasted normalized mean stiffness

Fig. 7. Mean material properties of blasted, open and closed cell sandwich specimens in dependance of the corrosion duration.

which was corroded for a total of 240 h, displayed a mean tensile strength of 0.56 MPa, resulting in an overall higher value than the two previous duration levels.

In comparison to the other closed cell core layer specimens, blasted core specimens showed a significantly lower maximum tensile strength, more on par with the open cell variants. Also, a relatively large scatter of measured tensile strengths was observed during the entire test series with this type of specimens. Due to this scatter of measurements no significant decrease of tensile strength with increasing corrosion duration could be determined for blasted core specimen variants. In Fig. 7(f), the normalized mean stiffness of blasted specimens is displayed. It can be seen that there was no significant decrease in stiffness with increasing corrosive exposure. As with the strength measurements, the large data scatter obscured any corresponding observations. Crack

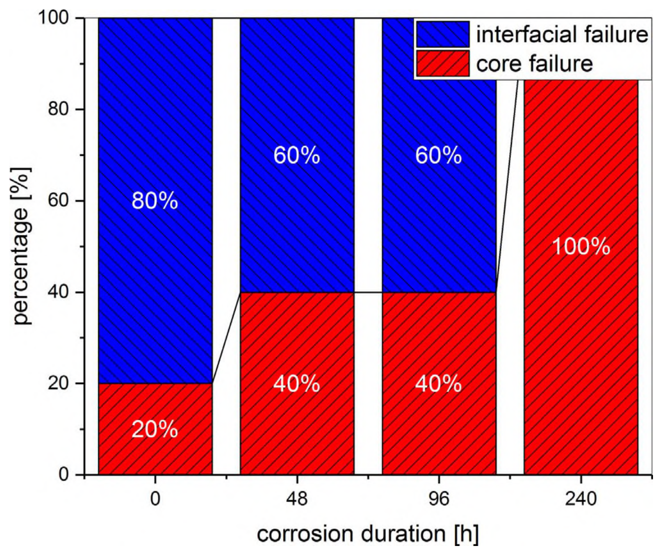


Fig. 8. Comparison of failure mode in dependence of corrosion duration for closed cell core sandwich specimens.

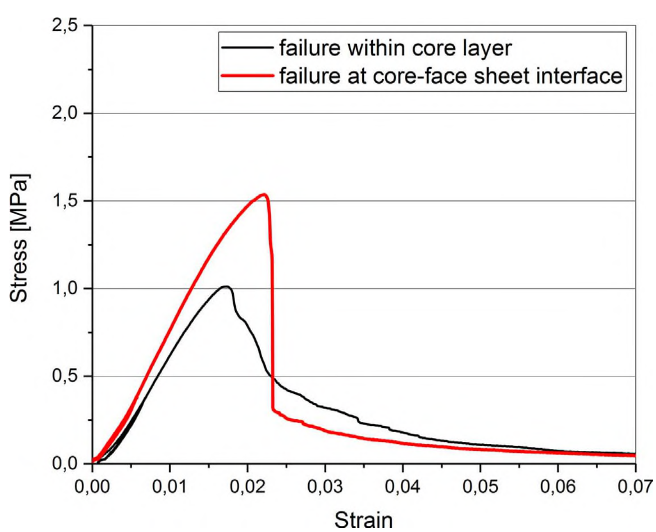


Fig. 9. Stress–strain curves of closed cell sandwich specimens with differing failure mode after 48 h of exposure to the corrosive environment.

propagation during mechanical testing was predominantly located at the core-face sheet interface, regardless of corrosion exposure.

The reduction of the mechanical characteristics of open and closed cell specimen variants after exposure to the salt spray environment indicates that corrosion processes took place, leading to erosion of the core material. This assumption is supported by the fact that large amounts of corrosion product were formed inside the foam core during salt spraying. However, as already stated, no corrosion damage, e.g. pitting corrosion of the aluminum foam, could be detected. According to Ashby [9], a lower ligament thickness t of the aluminum foam material would lead to a lower stiffness E, as can be seen in Eq. 1 for both open and closed cell foams (with E_s = Young's Modulus of the solid core material, l = ligament height).

$$E \propto E_s \frac{t^4}{l^4} \tag{1}$$

Furthermore, a reduction in ligament width would also result in higher stress levels inside the core material due to a smaller load bearing ligament cross-section. Therefore, it seems plausible that the reduction of tensile strength as well as stiffness was caused by the corrosive degradation of the aluminum foam. The increasing shift of the failure mode of closed cell sandwich specimens towards core failure (Fig. 8) also indicates erosion of the aluminum foam core. No similar shift in failure mode could be determined for the open cell or blasted core sandwich specimens. It seems like the core layer was the weakest part of the open cell sandwich specimens even in its reference state, with the corrosive process only further weakening it.

As for blasted core specimens, the observations stated above indicate that the core-face sheet interface was damaged during sand blasting. This lead to a drastically reduced interfacial strength, resulting in a weak connection between the individual layers. The large scatter observed during measurements may also stem from sand blasting, as it resulted in large foam cells which then lead to inhomogenous specimen characteristics. Although large amounts of corrosion products were noted in blasted core type specimens, no significant decrease in mechanical characteristics was observed, indicating that the interface strength was lower than the core strength, even after 240 h of exposure to the corrosive environment. The consistent crack propagation at the interface area regardless of corrosive exposure supports the assumption that salt spraying lead to corrosive degradation of the core layer, whereas the interface seemed to be widely unaffected by corrosive processes.

The stress–strain-curves of the tested sandwich specimens with Nomex-honeycomb core layer are shown in Fig. 10. Both the corroded and the reference specimens exhibited linear-elastic material behavior at the beginning of the testing procedure with a sudden drop in measured stress after reaching the respective tensile strength, accompanied by material failure inside the honeycomb core layer. The reference specimen reached the highest tensile strength (1.75 MPa) whereas the corroded specimens reached 1.63 MPa and 1.47 MPa, respectively. The absence of corrosion products within this type of specimens indicates that the decrease of tensile strength likely results from material scatter rather than salt spray testing. It is possible, that a different amount of structural elements was present within each Nomex specimen after cutting the specimens from the sandwich plate. Also, water absorption inside the face sheet material may have had a negative influence on the mechanical properties as well, as observed by [12]. The absence of any significant deviation of measured tensile strength of corroded honeycomb specimens in comparison to their reference counterparts therefore indicates that it was indeed galvanic corrosion that affected the mechanical properties of the aluminum foam core sandwich specimens.

5. Conclusion

The aim of this study was to characterize the influence of corrosion

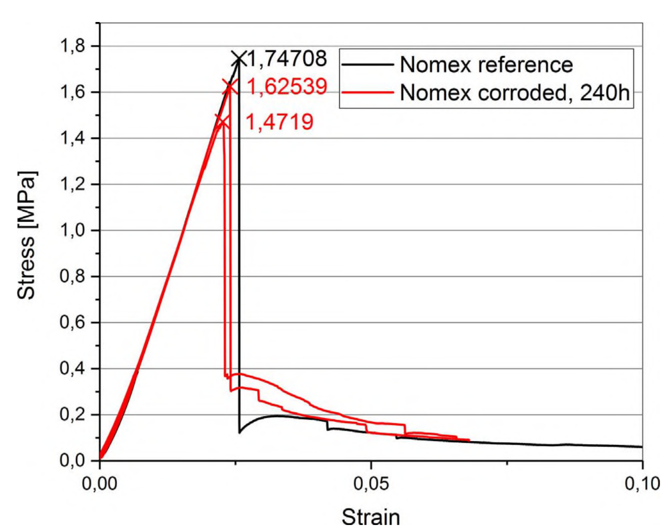


Fig. 10. Stress–strain curves of sandwich specimens with Nomex honeycomb core layer after 240 h of corrosion in comparison to a reference specimen.

on the mechanical properties of hybrid sandwich specimens made out of an aluminum foam core layer as well as CFRP face sheets. Sandwich specimens with different types of core material were corroded using the salt spray test for different levels of time, measured by X-ray computed tomography, and subsequently tested using the flatwise tension test for mechanical characterization. To confirm mass loss due to corrosion damage, a chemical cleaning procedure was used. Flatwise tension testing of corroded aluminum core sandwich specimens revealed a significant decrease in both tensile strength and stiffness for two out of three metallic core types. In comparison to the reference specimens, a decrease in mean tensile strength to up to 24% (open cell) respectively 30% (closed cell) of the initial value was measured. Measurements of specimen stiffness showed similar results. The remaining mean stiffness was found to be 55% (open cell) and 79% (closed cell), respectively. It is likely that the ligament thickness was reduced due to corrosion damage, which would explain both the reduction of tensile strength and stiffness. The following assessments support this assumption:

- All of the sandwich specimens with aluminum foam core (open and closed cell) showed a large amount of corrosion products inside the core layer, with cells close to the specimen surface being completely filled with corrosion product. With increasing corrosion duration, a higher amount of corrosion product was formed. This indicates that corrosion processes took place, with the precipitation of aforementioned corrosion products resulting from these. The absence of any kind of corrosion products within the Nomex honeycomb sandwich specimens seems to confirm that the corrosion products indeed resulted from the galvanic corrosion of the aluminum core layer, with no corrosion taking place in its absence. However, no distinct corrosion damage of the aluminum foam structure could be detected after removing the corrosion product layer. Therefore, a determination of mass loss was necessary to confirm the corrosive damaging of the aluminum core layer.
- For closed cell sandwich specimens, a shift in failure mode, from interface failure between core and face sheet layer to core failure, was detected, indicating a weakening of the core layer due to corrosion. No similar shift could be found for the open cell specimens, though. Every single open cell specimen failed within the core layer. The strength of the core layer of the open cell specimens seems to be lower than the interfacial strength of the core face-sheet interface, even in its reference, non-corroded state. It can be assumed though that the exposure to the salt spray environment further weakened the core layer, while the interface strength did not seem to suffer any significant strength loss. For the blasted core specimens, this leads to the assumption that the interface between core and face sheets was the weakest part of the sandwich due to damaging during sand blasting. Even after 240 h of salt spraying, the core strength was still higher than the interfacial strength, leading to crack propagation at the interface area. While this renders measuring the extent of corrosive degradation of the core area difficult, it still supports the above stated assumption that the interfacial strength is not significantly influenced by corrosion.
- In addition to sandwiches with metallic core layers, specimens with a Nomex honeycomb core layers were also tested for reference. This specimen type showed only a minor reduction in tensile strength following the exposure to the corrosive environment. Material scatter as well as water absorption within the face sheets was probably responsible for this. These results as well as the absence of any kind of corrosion product within the Nomex specimens seem to prove that the reduction of mechanical characteristics of aluminum foam sandwich specimens indeed results from corrosion.
- It was not possible to determine mass loss of corroded specimens using the cleaning procedure described in DIN EN ISO 8407:2014 due to a chemical reaction between the face sheet material and the nitric acid. Therefore, additional investigations using the X-ray computed micro-tomography were performed.
- The X-ray μCT measurements coincided with the determination of mass loss, supporting the observation of an absence of erosion within the aluminum core structure.
- In summary, both the strength and stiffness degradation caused by the corrosion damage could be measured and designated to the core structure. With increasing corrosion exposure time, the failure mode shifted from interface failure to core failure, and the stiffness decreased. The derived assumption of volumetric core degradation could, however, not be confirmed. Instead, it could be shown consistently both by mass measurements and by volumetric investigations, that no core erosion occured on a macroscopic level.

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References

[1] Immarigeon J-P, Holt RT, Koul AK, Zhao L, Wallace W, Beddoes JC. Lightweight materials for aircraft applications. Mater Charact 1995;35(1):41–67. http://dx.doi.org/10.1016/1044-5803(95)00066-6.

[2] Botelho EC, Silva RA, Pardini LC, Rezende MC. A review on the development and properties of continuous fiber/epoxy/aluminum hybrid composites for aircraft structures. Mater Res 2006;9(3):247–56. http://dx.doi.org/10.1590/S1516-14392006000300002.

[3] Adams DO, Webb NJ, Yarger CB, Hunter A, Oborn KD. Multi-functional sandwich composites for spacecraft applications: an initial assessment. Hampton, Va. and Springfield, VA: National Aeronautics and Space Administration, Langley Research Center and National Technical Information Service, Distributor; 2007.

[4] Crump DA, Dulieu-Barton JM, Savage J. Design and commission of an experimental test rig to apply a full-scale pressure load on composite sandwich panels representative of an aircraft secondary structure. Meas Sci Technol 2010;21(1):015108. http://dx.doi.org/10.1088/0957-0233/21/1/015108.

[5] Sokolov II, Kogan DI, Raskutin AE. Light-weight aggregates of sandwich structures. Polym Sci Ser D 2015;8(3):227–30. http://dx.doi.org/10.1134/S1995421215030156.

[6] Thomsen OT. Sandwich materials for wind turbine blades – present and future. J Sandwich Struct Mater 2009;11(1):7–26. http://dx.doi.org/10.1177/1099636208099710.

[7] Banhart J, Schmoll C, Neumann U. Light-weight aluminium foam structures for ships. In: Proc. conf. materials in oceanic environment (Euromat ’98) Vol. 1.

[8] Ishai O, Hiel C, Luft M. Long-term hygrothermal effects on damage tolerance of hybrid composite sandwich panels. Composites 1995;26(1):47–55. http://dx.doi.org/10.1016/0010-4361(94)P3629-F.

[9] Ashby MF, Medalist RFM. The mechanical properties of cellular solids. Metall Trans A 1983;14(9):1755–69. http://dx.doi.org/10.1007/BF02645546.

[10] Crupi V, Montanini R. Aluminium foam sandwiches collapse modes under static and dynamic three-point bending. Int J Impact Eng 2007;34(3):509–21. http://dx.doi.org/10.1016/j.ijimpeng.2005.10.001.

[11] Simone AE, Gibson LJ. Aluminum foams produced by liquid-state processes. Acta Mater 1998;46(9):3109–23. http://dx.doi.org/10.1016/S1359-6454(98)00017-2.

[12] Choi HS, Jang YH. Bondline strength evaluation of cocure/precured honeycomb sandwich structures under aircraft hygro and repair environments. Compos Part A: Appl Sci Manuf 2010;41(9):1138–47. http://dx.doi.org/10.1016/j.compositesa.2010.04.012.

[13] Banhart J, Seeliger H-W. Recent trends in aluminum foam sandwich technology. Adv Eng Mater 2012;14(12):1082–7. http://dx.doi.org/10.1002/adem.201100333.

[14] Jelovica J, Romanoff J, Ehlers S, Aromaa J. Ultimate strength of corroded web-core sandwich beams. Mar Struct 2013;31:1–14. http://dx.doi.org/10.1016/j.marstruc.2012.12.001.

[15] Fischer P, DeLuccia JJ. Effects of graphite/epoxy composite materials on the corrosion behavior of aircraft alloys. In: Christian JL, Stein BA, editors. Environmental effects on advanced composite materials 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International; 1976. http://dx.doi.org/10.1520/STP27780S. pp. 50-50-17.

[16] Gonabadi HI, Oila A, Bull S. Fatigue of sandwich composites in air and seawater. J Bio- Tribo-Corros 2016;2(2):265. http://dx.doi.org/10.1007/s40735-016-0043-2.

[17] Daniel I. Fabrication, testing and analysis of composite sandwich beams. Compos Sci Technol 2000;60(12–13):2455–63. http://dx.doi.org/10.1016/S0266-3538(00)00039-7.

[18] Rupp P, Elsner P, Weidenmann KA. Specific bending stiffness of in-mould-assembled hybrid sandwich structures with carbon fibre reinforced polymer face sheets and aluminium foam cores manufactured by a polyurethane-spraying process. J Sandwich Struct Mater 2017. http://dx.doi.org/10.1177/1099636217725250. 1099636217725250.

[19] Francis R. Galvanic corrosion: a practical guide for engineers. Houston, Tex: NACE

International; 2001.
[20] Wang W-X, Takao Y, Matsubara T. Galvanic corrosion-resistant carbon fiber metal laminates. In: 16th international conference on composite materials.
[21] Mandel M, Krüger L. Electrochemical corrosion studies and pitting corrosion sensitivity of a self-pierce rivet joint of carbon fibre reinforced polymer (cfrp) – laminate and en aw-6060-t6. Materialwiss Werkstofftech 2012;43(4):302–9. http://dx.doi.org/10.1002/mawe.201200945.
[22] Bellucci F. Galvanic corrosion between nonmetallic composites and metals: I effect of metal and of temperature. Corrosion 1991;47(10):808–19. http://dx.doi.org/10.5006/1.3585192.
[23] Peng Z, Nie X. Galvanic corrosion property of contacts between carbon fiber cloth materials and typical metal alloys in an aggressive environment. Surf Coat Technol 2013;215:85–9. http://dx.doi.org/10.1016/j.surfcoat.2012.08.098.
[24] Grote K-H, Feldhusen J. Dubbel. Berlin Heidelberg: Springer; 2007. http://dx.doi.org/10.1007/978-3-540-68191-5.
[25] Davis JR, editor. Corrosion of aluminum and aluminum alloys. Materials Park, OH: ASM International; 1999.
[26] Schindelin J, Arganda-Carreras I, Frise E, Kaynig V, Longair M, Pietzsch T, et al. Fiji: an open-source platform for biological-image analysis. Nat Methods 2012;9(7):676–82. http://dx.doi.org/10.1038/nmeth.2019.