

Numerical investigation on the influence of hydroxide production on the high-cycle fatigue behavior of clinched joints

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Abstract. Corrosion usually has detrimental effects on the longevity of metallic structures. Several corrosion mechanisms exist, which affect the metallic structures differently. Galvanic corrosion is a major corrosion phenomenon that occurs when two dissimilar metals are in contact with each other and with an electrolyte. Due to galvanic corrosion, the less noble metal dissolves which can shorten the service life of the metallic component significantly. However, recent research has shown that corrosion can have a beneficial impact on metal joints. Brief exposure of clinched specimens to a salt spray environment extends the corroded specimen's fatigue life. The present work introduces a simulation procedure which can numerically predict the effects of corrosion product formation on the fatigue life of clinched joints.

Introduction

Mechanical clinching is an innovative joining method that is especially suitable for combining dissimilar metals [1]. In short, the joint is created by pushing two metal sheets into a die with a punch. Joining dissimilar materials has the advantage that lightweight structures can be formed, which reduce material cost while simultaneously providing the necessary structural integrity. However, combining dissimilar metals causes the risk of galvanic corrosion. Due to the different electrochemical potentials of the metals, electrons are transferred from the less noble metal to the noble metal, leading to oxidation of the less noble metal. Material or component integrity is often compromised by this process, meaning that metal components need to be replaced over time.

A common method to prevent material degradation by corrosion is to use a sacrificial anode or cathodic protection. An overview of the affection of clinched joints by corrosion is given in [2]. Recent literature [3] has shown that a brief exposure of clinched specimens to a corrosive environment can also have beneficial effects to the specimen's fatigue life. The EN AW-6014/HCT590X+Z specimens have been corroded for three weeks prior to the fatigue testing. The authors attributed the observed effect to the corrosion products building up in the gap area between the joined metal sheets. They provided a simple mechanical model that shows a change in the load bearing capabilities of the clinched specimen when the gap size is reduced. Previously, the influence of a salt spray environment on the load bearing capabilities of clinched joints has been experimentally studied in Ref. [4]. It was shown via shear tests that the load bearing capabilities of the joints decreased with the exposure to the salt spray.

Numerically, both corrosion and fatigue phenomena have been thoroughly studied in the literature. Mathematical models exist that describe corrosion and material fatigue very well. Modeling metal dissolution can be performed by using different approaches. Phase field models rely on solving the coupled Allen-Cahn and Cahn-Hilliard equations. The boundary between metal and electrolyte does not need to be moved by applying a distinct displacement. Thus, this approach

is very suitable for modeling complex geometries or surfaces that combine during the simulation procedure.

In Ref. [5] a phase field model is used to study multiple corrosion phenomena, such as pitting corrosion in a hybrid joint. In Ref. [6], a phase field model is used to simulate stress corrosion cracking. In this computational model, the cracks initiate from pits. Pit growth under mechanical and environmental influence is studied. Another popular modeling approach for corrosion is the level set method, which is also very suitable for the simulation of merging surfaces. In Ref. [7], a level set model is presented, where among others, the lacy cover formation of pits is studied. The Arbitrary Lagrangian-Eulerian method to simulate the anodic dissolution is also widely used in the literature. A thorough overview of this method is given in Ref. [8].

High-cycle fatigue in metallic materials has been mathematically described and simulated in Ref. [9]. There is a research gap in the literature, where both concepts of galvanic corrosion and high-cycle fatigue are coupled and applied to clinched joints.

The present work expands on the idea that corrosion products improve the load bearing capabilities of clinched joints. First, a computational model is introduced, which simulates the formation of corrosion products and their influence on the fatigue life of clinched joints. Then, the test case is introduced, and the computational model is described. The results of the model are given and are discussed. Finally, a summary, as well as a short conclusion are given.

Test Case Description and Computational Model

In this section, the challenges in modeling of the corrosion phenomenon are described. The considered geometry for the test case is shown in Fig. 1. Modeling the positive effects of galvanic corrosion on the fatigue life of clinched joints requires a coupled electrochemical-mechanical model. The electrochemical part of the model describes the corrosion behavior of the clinched joint in the salt spray environment, while the mechanical part of the model describes the mechanical response of the joint under applied loads. In order to achieve the chemo-electro-mechanical coupling, three major steps are defined. (i) Simulate the hydroxide layer growth which is caused by galvanic corrosion. (ii) Simulate the load bearing during cyclic loading, which is affected by the hydroxide layer thickness, and (iii) numerically predict the fatigue life of the corroded clinched joint.

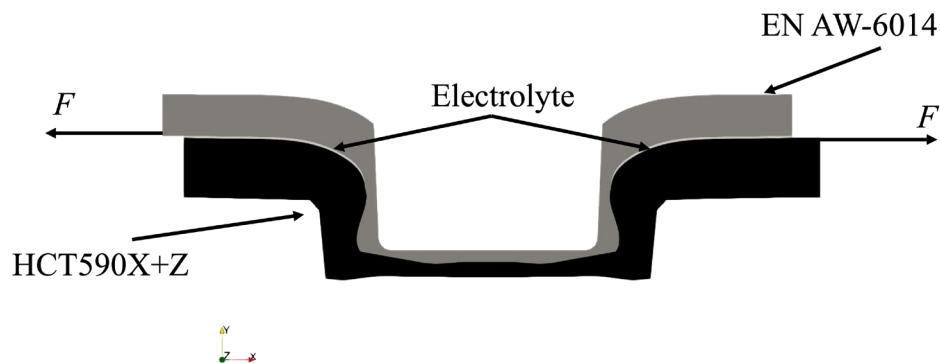


Fig.1: Two-dimensional computational domain of the clinched joint.

Performing step (i) usually requires a detailed model that accurately describes the corrosion behavior of the clinched joint. The corrosion behavior of EN AW-6014/HCT590X+Z/Electrolyte is reflected by the constituents' electric potentials and open circuit current densities. With those parameters, a corrosion velocity of the less noble metal's surface can be determined. During the dissolution of the less noble metal, metal ions are oxidized and dissolve into the electrolyte. This procedure is described by Eq. 1



Depending on the pH of the electrolyte, hydroxide ions are produced at the cathode. This process is described by Eq. 2



Metal ions and hydroxide ions in the electrolyte react and form metal hydroxides, which usually have a low solubility and thus precipitate. The current work uses a simplified model to mimic the corrosion product formation. The corrosion behavior is assumed as follows. The zinc layer on the surface of HCT590X forms a galvanic couple with the aluminum sheet. As shown in [3], the zinc layer is less noble than the aluminum alloy and dissolves into the electrolyte. The zinc hydroxide production is modeled as a growing layer on top of the surface of HCT590X+Z. To achieve this, the geometry is divided into solid and liquid domains. Solid domains are the metal sheets and the metal hydroxide layer, and liquid domains are the electrolyte in the gap areas. This is implemented by using one concentration field for the solid (c_{solid}), and one concentration field for the liquid (c_{liquid}).

The normalized concentrations represent the phase fractions, i.e., they vary between 0 and 1, and thus reflect the different phases of the geometry, i.e., solid and liquid. In areas where c_{solid} is 1, c_{liquid} is 0, and vice versa. The transition between the liquid and the solid phases is resembled by a diffuse interface, see Fig. 2.

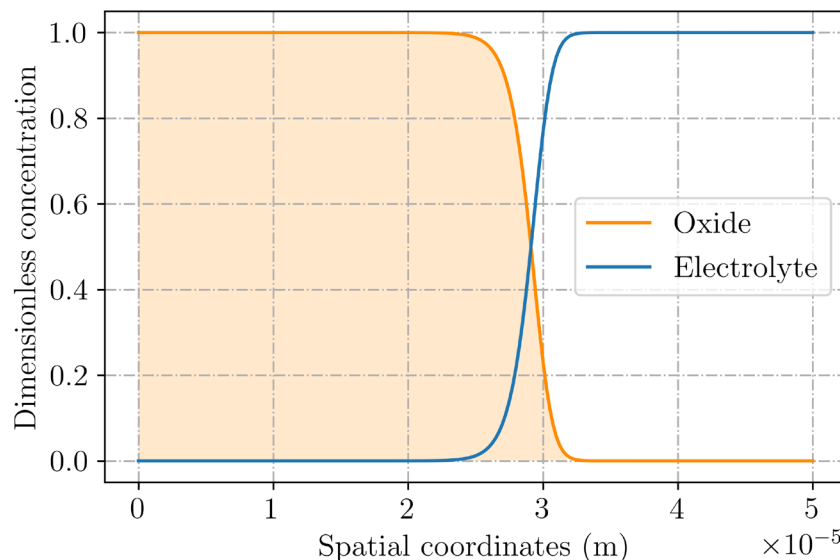


Fig. 2: One-dimensional interface between the solid phase (oxide) and the liquid phase (electrolyte) of the domain.

The conversion of the liquid domain to the solid domain in the gap area is realized by using a reaction term R_α . The system of equations is as follows. For the liquid and solid domains, a mass balance (Eq. 3) is used, respectively.

$$\frac{\partial c_\alpha}{\partial t} = D_\alpha \nabla^2 c_\alpha + R_\alpha \text{ with } R_\alpha = k c_{solid} c_{liquid} . \quad (3)$$

Here, c_α is the concentration of either liquid or solid, D_α is the diffusion coefficient, and R_α the reaction term. k is the rate constant. In this model, D_α and k define the size and the velocity of the moving interface during the phase transition. With the introduced chemical model, the hydroxide layer growth due to galvanic corrosion can be described.

In step (ii), the chemical field is coupled to the mechanical field. The mechanical model is based on linear elasticity. The coupling between the chemical and the mechanical field is achieved by multiplying the Young's modulus E with the solid phase concentration, resulting in distributions, which are shown in Fig. 3. A numerical problem arises where the solid phase is zero, since the resulting Young's modulus there would also be zero. This problem is solved by constraining the solid phase concentration in the liquid phase to very small values larger than zero.

In order to simulate the fatigue behavior, two load cases were applied to the clinched joint. One load, which represents the maximum force, and one load, which represents the minimum force during cyclic testing. The resulting stress fields can then be used in step (iii) to determine the fatigue life of the clinched joint.

In step (iii), the high cycle fatigue model, originally introduced by Lemaitre [9], is used. It assumes a representative volume element (RVE), which contains a micro inclusion. The RVE exhibits elastic behavior, while the micro inclusion behaves elastic plastic. For each loading cycle, a damage increment is numerically determined, which accumulates in a damage variable D . Upon reaching a critical value, i.e., $D = 1$, material failure occurs, and cracks can form.

Usually, the damage variable is calculated, e.g., for each node in the finite element mesh. However, computational costs can be reduced by limiting the high-cycle fatigue calculations to the location of the largest von Mises stress in the clinched joint. A similar approach has been used in [10]. A brief summary of the two-scale high-cycle fatigue model by Lemaitre is given in the following. The model considers two scales. The macro scale, which only considers elastic behavior, and the micro scale, where plastic strains occur. Variables on the micro scale are denoted with the superscript $()^\mu$. Stresses from the macro scale σ_{ij} are transformed to the micro scale σ_{ij}^μ by a localization parameter a (Eq. 4). The stresses from the macro scale are obtained by finite element simulations.

$$\sigma_{ij}^\mu = \sigma_{ij} - aE\varepsilon_{ij}^{\mu p} \quad \text{with } a = \frac{1-\beta}{1+\nu} \quad \text{where } \beta = \frac{2(4-5\nu)}{15(1-\nu)} \quad (4)$$

Here, E is the Young's modulus, $\varepsilon_{ij}^{\mu p}$ is the plastic strain on the micro scale, and ν is the Poisson ratio. During the static loading, a yield function f^μ (Eq. 5)

$$f^\mu = (\tilde{\sigma}_{ij}^\mu - X_{ij}^\mu)_{\text{eq}} - \sigma_f \quad (5)$$

is evaluated.

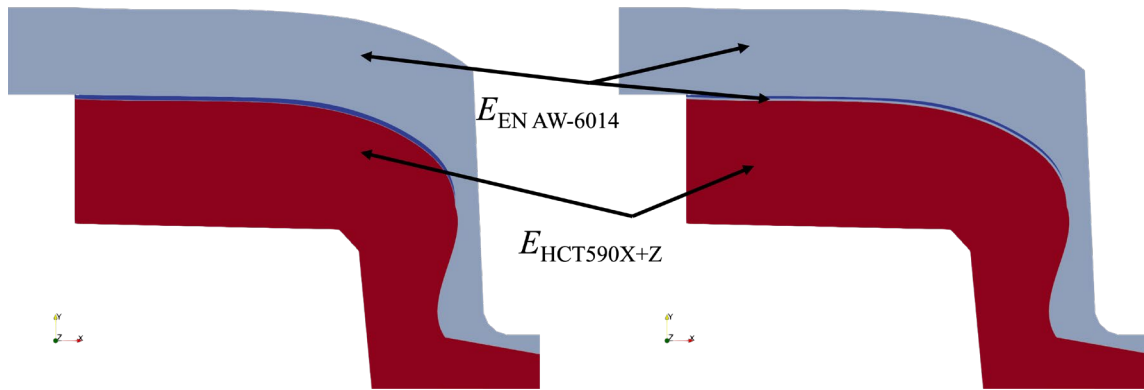


Fig. 3: Young's modulus distribution for the initial domain (left) and for the growing hydroxide layer (right).

$\tilde{\sigma}_{ij}^\mu$ is the effective stress on the micro scale, which is defined by $\tilde{\sigma}_{ij}^\mu = \sigma_{ij}^\mu / (1 - D)$. X_{ij}^μ is the backstress tensor, which accounts for kinematic hardening on the micro scale, and σ_f is the fatigue limit. $(\)_{eq}$ is the equivalent (von Mises) expression of the function inside the brackets. If the value of the yield function is zero or larger than zero, i.e., $f^\mu \geq 0$, plastic strains occur. The damage rate \dot{D} of the current cycle can then be calculated by Eq. 6

$$\dot{D} = \left(\frac{Y^\mu}{S}\right)^s \dot{p}^\mu, \text{ where } \dot{p}^\mu = \frac{\lambda^\mu}{(1-D)}. \quad (6)$$

Here, Y^μ is the strain energy density release function, S is the damage strength, s is the damage exponent, and λ^μ is the plastic multiplier. Y^μ usually depends on a closure parameter h , which accounts for the closure of micro defects under compression. This means that the damage increments are smaller in areas where compression occurs.

In summary, the fatigue life of pre-corroded and non-corroded clinched joints can be numerically predicted by (i) simulating the hydroxide layer growth due to galvanic corrosion, (ii) simulating static loading during the fatigue tests and identifying the area where the largest stress occurs, and (iii) performing high-cycle fatigue calculations with the highest stress as an input. Both models for step (i) and (ii) are coupled and implemented within a finite element framework. Coupling means that the growing hydroxide layer is included in the static loading simulations. The high-cycle fatigue damage model is implemented via a python script, where the closed form solution shown in [11] is applied.

Influence of the Hydroxide Production on the Fatigue Life of Clinched Joints

In this section, the results of the simulation procedure are given and discussed. Fig. 4 shows the hydroxide layer thickness at different time stamps obtained from step (i). The small gap between both metal sheets is filled with corrosion products and thus shrinks in its size. Metal dissolution and corrosion product formation occur at the same time.

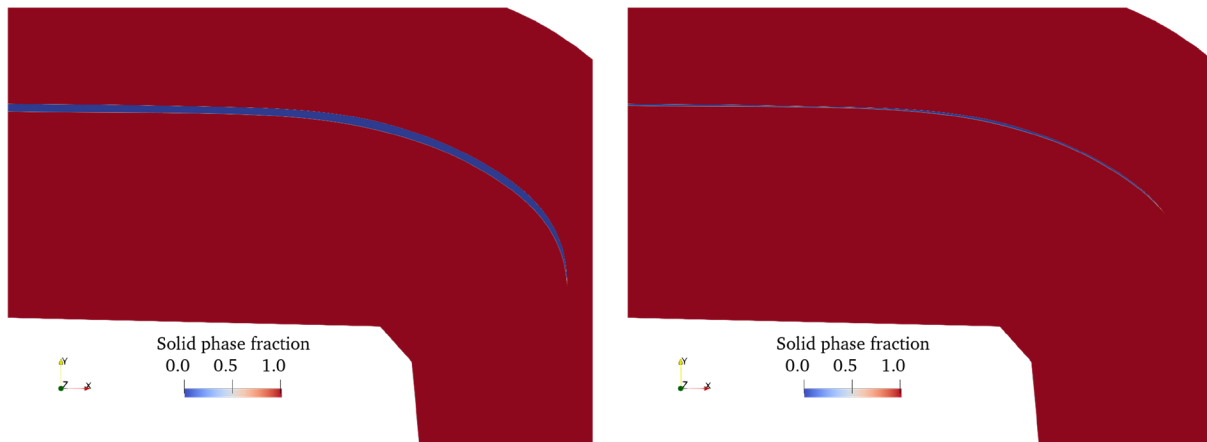


Fig. 4: Initial solid phase fraction (left) and solid phase fraction after 1200 s (right).

In the current model, metal dissolution is neglected. The specific volume of the corrosion product zinc hydroxide is much larger than the specific volume of the dissolving zinc, which is why only the hydroxide layer growth is considered. The time scales of the computational model do not necessarily reflect the real-world corrosion behavior of the clinched joint in the salt spray environment. For example, the clinched specimens were corroded for three weeks in the salt spray chamber in [3].

No details on the intermediate states of corrosion (e.g., hydroxide layer thickness) were given. It is thus not possible to precisely derive the growth rate of the hydroxide layer from the performed experiments. However, the parameters of the model (D , k) can be adapted to increase or slow down the hydroxide production rate to accurately reflect the actual corrosion behavior.

Furthermore, the presented results align very well with experimental findings, i.e., the formation of corrosion products leads to an overall better fatigue life. The introduced model shows the potential to accurately reflect the real-world behavior. Its parameters, however, have to be determined by further experimental investigations. For example, it is expected that mass transfer of the dissolving metal ions is slowed down by the growing hydroxide layer. This effect can be captured by a time dependent diffusion coefficient D . The hydroxide layer growth should thus slow down over time. In the current model, the growth rate is assumed to be constant, as shown in Table 1.

Table 1: Results of the high-cycle fatigue calculations with different hydroxide layer thicknesses.

Time t [s]		0	50	100	150
Hydroxide layer thickness [μm]		0	6	12	18
Number of cycles until failure	Force amplitude 700 N	1211	2397	4678	8602
	Force amplitude 500 N	21513	43338	84602	162120

The results obtained from step (ii) are shown in Fig. 5. In the left plot, no hydroxide layer is considered and consequently, large stresses occur in the left neck area. The right plot shows the von Mises stress for the same applied load. In this case however, the gap is fully closed with corrosion products. The overall occurring stresses in the final configuration are lower compared to the configuration without corrosion products. It can be concluded that the growing hydroxide layer influences the load bearing behavior of the clinched specimen. Near the tip of the left gap, very large stresses were observed. These large stresses originate from the fact that the clinched specimen is simulated as a continuous body with different material properties, i.e., no contact formulation was applied yet. For the rest of the proposed modeling procedure, these large stresses at the tip of the left gap were not considered.

In step (iii), the results from the static loading simulation are used in the high-cycle fatigue calculation. For this, two force amplitudes of 700 N and 500 N, respectively, were used in step (ii). Table 1 summarizes the calculated results. A clear trend is recognizable, a thicker hydroxide layer results in slower damage accumulation. This means that more loading cycles can be endured by the clinched specimen before material failure occurs. In 50 s simulation time of hydroxide layer growth, the number of cycles until failure roughly doubles.

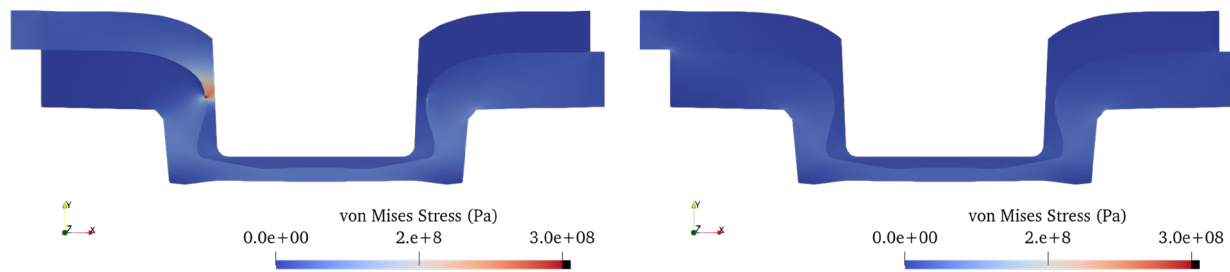


Fig. 5: von Mises stress of the initial configuration with no hydroxide layer (left) and von Mises stress of the final configuration with a fully closed gap (right).

Conclusion

In this work, a modeling procedure was introduced that can numerically simulate the impact of a hydroxide layer production on the fatigue life of clinched joints. It was shown that corrosion products enlarge the contact area of the metal sheets in the clinched joints, ultimately reducing the mechanical stresses. This stress reduction leads to an improved fatigue life. The present model has some shortcomings, which will be addressed in future research. The hydroxide layer production in the model does not accurately reflect the real-world time scale. This can be addressed by adjusting the reaction constant and the diffusion coefficients of the two species. Furthermore, the electrochemical behavior of the galvanic pair EN AW-6014 and HCT590X+Z is not fully described. This means that the hydroxide layer production is currently not influenced by the metals' electric potentials and is thus uniform along the metal surface.

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