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High-Performance Static Seal Solutions for Compact Grooves in E-Mobility

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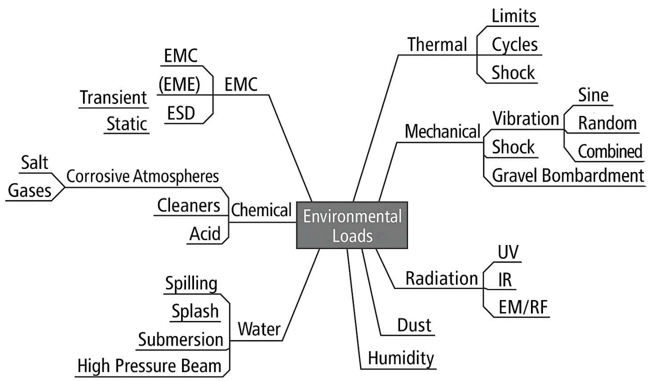
The increasing miniaturization of e-mobility and e-bike systems places stringent demands on static seals. Battery enclosures, motor housings, connectors, and sensor interfaces must achieve high ingress protection in smaller packaging spaces, with sealing grooves significantly reduced compared to conventional sealing systems. This reduction in geometry intensifies several coupled challenges: maintaining sufficient and uniform contact pressure for sealing across wider tolerance stacks, preventing crevice formation that can drive localized corrosion, and ensuring long-term material stability under thermal cycling, vibration, and exposure to electrolytes, road salt, and cleaning agents. Traditional design rules and test protocols, customized for larger cross-sections and more forgiving groove volumes, do not directly translate to these constraints. This work presents a design and validation framework for static seals in miniaturized e-mobility applications that explicitly co-optimizes sealing reliability and corrosion protection.

1 Introduction

Electronic control units (ECU) of electric cars installed in e-axels are exposed to various environmental loads [1] in the field like we can see in Figure 1, which during active operation are exposed by functional environmental loads. In sealing technology, a robust design is characterized by the ability of the selected sealing elements to reliably withstand damage-relevant mechanical, thermal, and chemical loads, such that their functional capacity exceeds the loads encountered during operation [1].



[1]

Figure 1. Definition of environmental loads on static seal [1]

The magnitude of the environmental load is essentially determined by the installation location within the vehicle Figure 2. It is therefore clear that products installed inside the vehicle cabin, for example, are only exposed to low corrosive loads, which are typically introduced by the driver or passengers.

Nowadays, in new generations of electric and hybrid vehicles, ECUs are mostly installed outside the passenger cabin. As a result, they are exposed to increased pollution and harsher weather conditions. Additionally, new case designs for electronic units are often made from aluminium alloys containing copper (Cu) to improve casting properties and optimize manufacturing costs. However, aluminium alloys with copper exhibit significantly lower corrosion resistance [2], [3].

Therefore, conventional static seal solutions must be optimized to withstand these more aggressive environmental conditions.

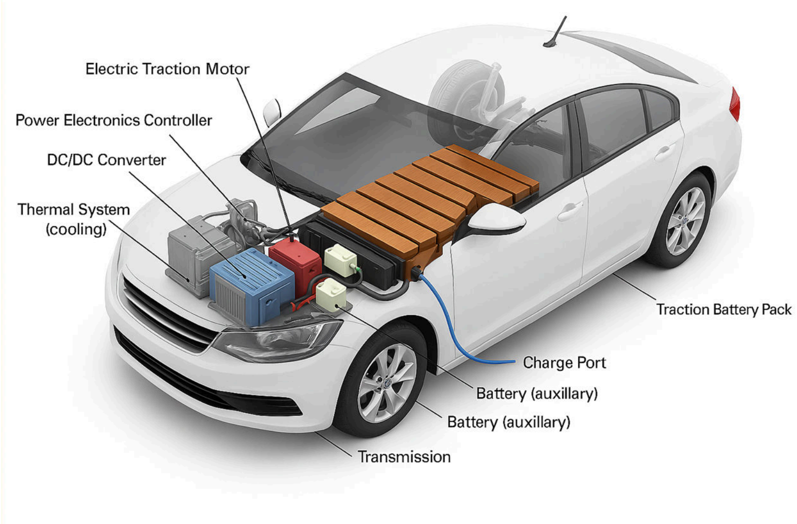


Figure 2. Positions od electronic components in vehicle

The most problematic situations arise when electronic devices are located in the engine compartment, particularly near the floor or in the area of the wheels, as these locations are especially exposed to spray water enriched with salt (NaCl) during the winter months. As a result, corrosive failure mechanisms can be initiated within a short period of time. Additionally, engine covers designed to reduce noise and vibrations—often made from materials such as EPDM foam (Fig. 3)—can collect salty water from the road, extending the exposure of seal element to corrosive salt water.

Figure 3. EPDM foam cover can collect salt water and expand period of corrosion attack

In his study, Bader [4] analyses the failure mechanism of corrosion-induced undercutting at static sealing interfaces and discusses the associated risk of secondary damage. From a materials science perspective, these findings demonstrate that the functional reliability of sealing systems operating in corrosive environments can only be ensured by systematically considering the following material- and interface-related aspects:

- Corrosive stress from the environment,
- Design of the sealing system (seal gap, sealing element),
- Material selection of the housing components.

The installation position of sealing systems is typically predefined by the OEM, thereby imposing strict boundary conditions related to exposure, loading, and media contact. Economic constraints favor the widespread use of aluminum die-cast alloys as structural materials; however, these materials exhibit limited corrosion resistance and pronounced surface sensitivity in chemically aggressive environments. As a consequence, the primary variable available for performance optimization resides in the material- and interface-specific design of the sealing system.

The present study illustrates how a systematic design-driven approach, incorporating material compatibility, and corrosion-relevant degradation mechanisms, enables the optimization of an existing sealing system. This approach ensures sustained sealing functionality and structural lifetime integrity over the required service life, even in exterior service conditions characterized by elevated corrosion risk.

2 Overview of Standard Seal Solutions for Static Seal Applications

Corrosive undercutting of seals is frequently discussed in common terminology [4] [5], often with exclusive focus on the elastomer sealing element. However, the surrounding environment also plays a crucial role in this process. Therefore, it is more practical to consider the whole sealing system, which consists of both from one side sealing element and from another side the housing parts made from metal or some polymer material.

According to literature information [6] (see Figure 4), the design of the housing halves determines the inlet housing gap defined by the housing gap length L and gap height H in front of the sealing element and thus the penetration path of the electrolyte.

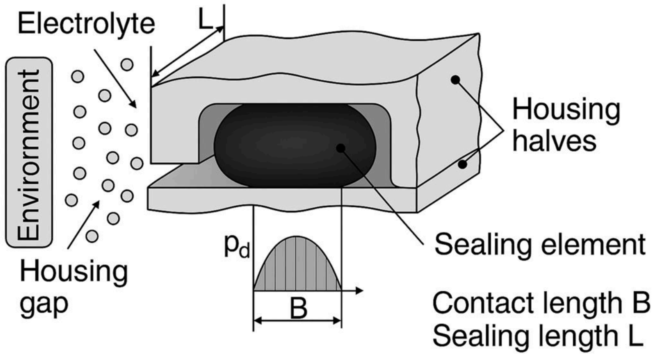


Figure 4. Definition of static seal system

The elastomeric sealing material strives to return to its original shape after deformation. This creates an initial sealing pressure p_D in the contact area between the sealing surfaces and the sealing ring defined as sealing contact area B. For O-rings, the pressure distribution perpendicular to the sealing length in the unpressurized state approximately has the shape of a parabola. When media pressure is applied during operation, it adds to the surface pressure resulting from the compression of the O-ring. As a result, the maximum sealing pressure is always greater than the pressure to be sealed.

The process of corrosion-induced undercutting of a static sealing system can be subdivided into five successive stages (Figure 5). The individual stages are described in detail in [6]. Initially, an electrolytic medium must reach the entrance region of the housing gap (stage 1) and subsequently penetrate along the housing gap toward the sealing element (stage 2). After a characteristic initiation time (stage 3), the mechanism of corrosion-driven seal undercutting becomes effective (stage 4). Once the corrosive attack extends over the entire sealing contact length, the static sealing system is considered fully undercut and functionally compromised (stage 5).

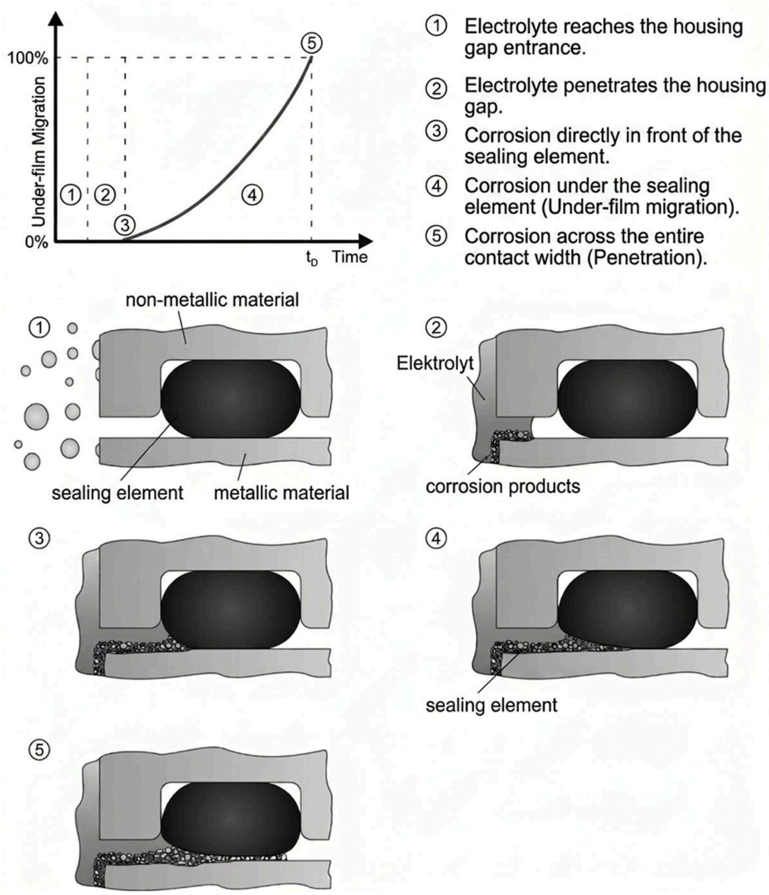


Figure 5.The process of corrosion-induced undercutting of a static sealing system

This means that no undercutting of the sealing system occurs in stages 1 and 2, since no electrolytic medium has yet penetrated as far as the sealing element. The ingress of liquid into the housing gap depends, from a design and construction perspective, on two key aspects:

- the design of the periphery of the sealing interface,
- the geometry and design of the housing gap.

The task of our scientific research was to develop seal solution that will close the gap before entrance of electrolyte liquid in the groove to achieve better seal performance in comparison with conventional static seal solutions.

Once corrosion-induced undercutting has been initiated, the duration until full penetration of the sealing system is governed predominantly by the geometrical design and dimensional configuration of the sealing element. In research [6], experimental studies using sealing profiles of different geometries and sizes under saltwater immersion conditions revealed a quantitative relationship between the time to penetration of the sealing interface and the so-called corrosion penetration resistance R_{DW}.

It was shown that the penetration time increases with increasing penetration resistance. The corrosion penetration resistance R_{DW} of a sealing system is defined as the integral of the contact pressure distribution $p_D(x)$ over the contact length B as described in equation 1.

$$R_{Dw} = \int_{x=0}^{B} p_D(x)dx \quad (1)$$

As an approximation described in equation 2, the corrosion penetration resistance can also be determined from the product of the contact length B and the mean sealing contact pressure $p_{D,m}$

$$R_{Dw} = B \cdot p_{Dm} \quad (2)$$

Verification if the designed sealing system is capable of withstanding the expected life time must therefore be carried out by means of an appropriate corrosion test. This test, which is generally performed under cyclic conditions, is considered an indicator test. Consequently, failure in such a test does not allow a direct prediction of field service life; however, it enables the identification of potential weaknesses in the design.

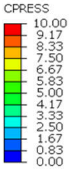
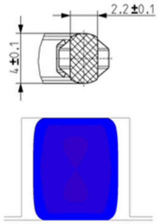
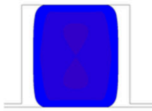
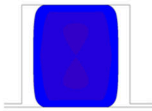
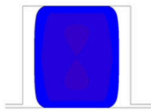
3 Develop of new static seal profile

The development of an advanced sealing concept with improved functional performance requires the establishment of a reference configuration based on a conventional, industry-proven seal design. Such a reference enables systematic evaluation and design-driven optimization with respect to geometry and elastomer material selection.

Accordingly, the first section of this chapter introduces and characterizes a standard square-profile seal that is widely used in static sealing applications within the automotive industry and serves as the baseline for subsequent design modifications.

As shown in Table 1, the standard square static seal made from Polyacrylate elastomer (ACM) in hardness of 70 Sh-A was analysed using finite element methods in a function of temperature. Groove tolerances were not considered in the simulation to facilitate a more fundamental interpretation of the results.

Table 1. Corrosion resistance value of standard square seal

Temp.	23 °C	-40 °C	80 °C	120 °C
Gap 0 mm 				
B (mm)	2,2	1,6	3	3,3
P D,m (N/mm2)	1,79	1,48	2,9	4,1
R DW (N/mm)	3,938	2,368	8,7	13,53

The results presented in Table 1 indicate that temperature has a significant influence on both the contact width of the sealing element and the resulting contact pressure. Variations in contact pressure and contact width directly affect the corrosion resistance performance of the sealing system.

Based on the preliminary calculations summarized in Table 1, it is evident that increasing temperature leads to notable changes in the sealing contact conditions. Therefore, the primary development objective is to design a sealing concept that maintains a nearly constant contact width with minimal sensitivity to temperature variations.

As observed in the corrosion test results, an increase in temperature leads to a more aggressive corrosion mechanism. Elevated temperatures accelerate the corrosion process by enhancing chemical reaction kinetics and increasing the penetrability of corrosive media, thereby resulting in a higher corrosion attack on the system. [5]

The predefined development targets for the new seal design were defined as follows:

1. Achieve a sufficiently wide contact area that remains stable over the operating temperature range.
2. Incorporate additional sealing nipples at the seal ends to close gaps between housing components and prevent saltwater penetration into the seal groove.
3. Increase the flexibility of the central region of the seal cross-section by reducing the material volume, thereby providing additional free space within the groove and compensating for thermal expansion at elevated temperatures.

Figure 6 illustrates the first design iteration of the newly developed sealing solution. In this initial concept, minor geometric modifications were introduced, particularly at the seal ends, to improve gap closure and contact stability. The base material was Hydrogenated Nitrile Butadiene Rubber (HNBR) with hardness of 60 Shore A to enhance flexibility and improve the adaptability of the seal under thermal loading conditions.

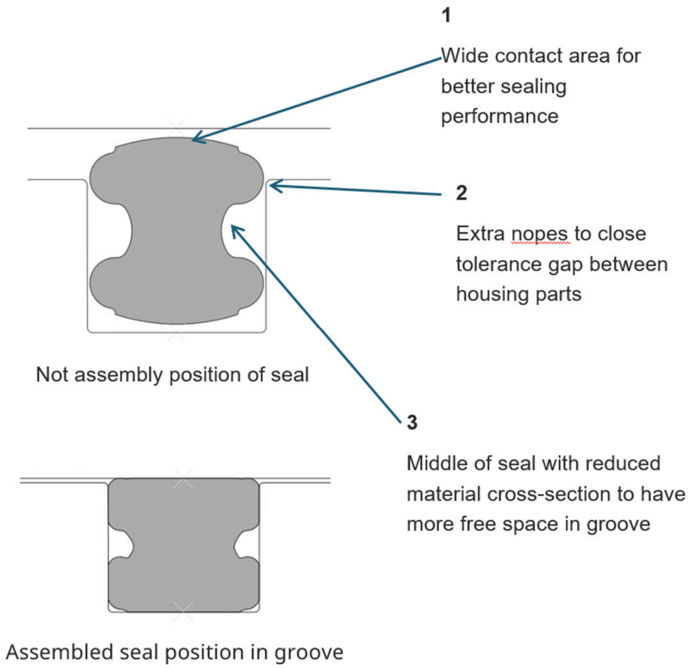


Figure 6. New profile seal development with new features

The finite element method (FEM) results obtained from the numerical simulation are presented in Figure 7. The analysis indicates that the sealing element establishes contact forces in both axial and radial directions, producing a stable and continuous contact pressure distribution at the seal–counterface interface. From a tribological standpoint, this combined loading condition enhances interfacial conformity and contact stability, thereby minimizing the formation of preferential leakage paths along the sealing interface. [7], [8]

The established contact pressure effectively inhibits saltwater penetration into the seal groove by maintaining a mechanically closed interface under operating conditions. This reduction in fluid ingress limits electrochemical exposure of metallic components, thereby improving the corrosion resistance of the sealing system. Consequently, the simulated contact mechanics demonstrate that the seal geometry and material response contribute to improved sealing efficiency and long-term durability in corrosive environments. [8]

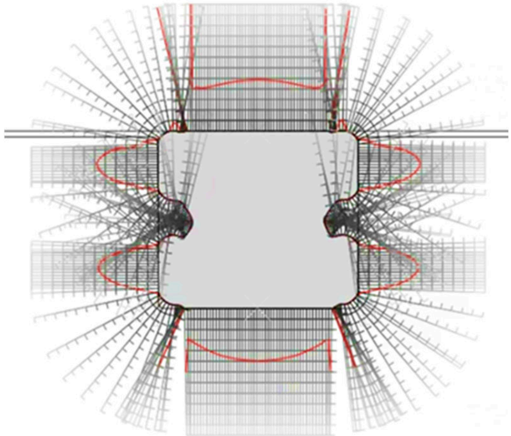
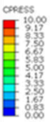
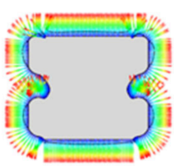
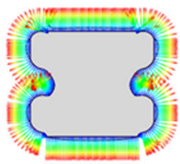
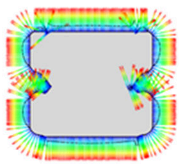
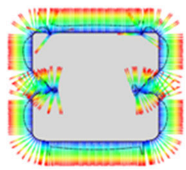


Figure 7. FEM calculation of new profile seal with contact forces in axial and radial direction

Compared with the conventional solution, the increased corrosion resistance values summarized in Table 2 reflect the effectiveness of the improved seal design in maintaining sealing integrity and minimizing electrolyte penetration at the seal interface.

Table 2. Corrosion resistance value of new developed profile seal

Temp.	23 °C	-40 °C	80 °C	120 °C
Gap 0 mm 				
B (mm)	3,5	3,5	3,5	3,5
P D,m (N/mm2)	1,9	1,67	3,3	4,5
R DW (N/mm)	6,65	5,85	11,55	15,75

An important consideration in modern automotive design is the increasing use of recycled aluminium alloys for gearbox housings, as well as aluminium alloys containing copper to improve castability and manufacturing efficiency. However, both material systems typically exhibit reduced intrinsic corrosion resistance. In chloride-rich environments, such as saltwater exposure, these alloys are particularly susceptible to localized corrosion phenomena, including corrosion undercutting beneath sealing elements. [2], [3] The presence of aggressive electrolytes can promote crevice corrosion at the seal–housing interface, especially when sealing integrity is insufficient. In applications where design constraints permit, the application of an additional grease layer containing corrosion inhibitors within the seal groove can be employed for static sealing systems. This approach further limits electrolyte ingress and enhances resistance to corrosion undercutting by providing both a physical barrier and chemical protection. [9]

Corrosion testing has demonstrated positive results for the newly developed sealing solutions, particularly in applications requiring protection of electrical housings against saltwater exposure. Notable improvements were observed in e-mobility applications, including sealed electric drive housings and static sealing of E-bike electric motors. These results confirm that the optimized seal design and material selection significantly improve corrosion resistance and long-term reliability in aggressive environmental conditions.

4 Conclusion

In this study, a systematic design approach combining finite element analysis and corrosion testing was applied to improve the performance of static sealing systems used in automotive and e-mobility applications. Analysis of a conventional ACM square seal revealed that temperature-dependent changes in contact conditions significantly compromise corrosion resistance, particularly in housings manufactured from recycled aluminium and Al–Cu alloys.

A new seal profile was developed to address these limitations by stabilizing contact width, improving gap closure, and enhancing flexibility through material and geometric optimization. FEM simulations demonstrated improved axial and radial contact force distributions, while experimental results confirmed a substantial increase in corrosion resistance compared to the reference design.

The developed sealing solution provides an effective design strategy for improving durability, corrosion resistance, and reliability of static seals in aggressive environments. The approach presented in this work offers practical guidance for seal and housing designers seeking robust solutions for next-generation automotive and e-mobility systems.

5 Nomenclature

Variable	*Description*	*Unit*
R_{DW}	Corrosion resistance value	[N/mm]
$p_{D,m}$	Middel contact pressure	[N/mm^2]
B	Seal contact width	[mm]
L	Seal contact length	[mm]

6 References

[1] B. Stiegler, S. Bader and V. Schweizer, “Erhöhung der Robustheit gegen korrosive Dichtungsunterwanderung: Ein Beispiel aus der Automobilelektronik,” *International Sealing Conference,* no. 19 ISC, p. 6, 2016.

[2] S. Gudic, L. Vrsalovic, J. Krolo, A. Nagode, I. Dumanic Labetic and B. Lela, “Corrosion Behaviour of Recycled Aluminium AlSi9Cu3(Fe) Machining Chips by Hot Extrusion and Thixoforming,” *Sustainbility ,* p. 19, 2024.

[3] C. Monticelli, F. Zanotto, A. Balbo, V. Grassi, A. Fabrizi and G. Timeli, “Corrosion behavior of high-pressure die-cast secondary AlSi9Cu3(Fe) alloy,” *Corrosion Science,* p. 14, 2022.

[4] S. Bader, W. Haas and B. Stiegler, “Auslegungskriterien zur Vermeidung korrosiver Durchwanderung statischer Dichtungen,” *International Sealing Conference,* pp. 507-512, 2014.

[5] P. Roberge, Handbook of Corrosion Engineering, New York: McGraw-Hill, 2000.

[6] S. Bader, W. Haas, B. Stiegler and L. Hörl, Statische Dichtsysteme unter korrosiver Belastung - Einfluss der Gehäusespaltgeometrie, Mannheim : ISGA-TEC, 2014, 2015, pp. 100-111.

[7] L. K. Massey, The Effects of UV Light and Weather on Plastics and Elastomers, 13 Eaton Avenue Norwich, NY 13815 : William Andrew Publishing , 2007.

[8] P. A. Schweitzer, Corrosion of Polymers and Elastomers, Taylor & Francis Inc; 2. Edition, 2006.

[9] A. K. Bhowmick, Current Topics in elastomers research, 6000 Broken Sound Parkway NW, Suite 300: CRC Press Taylor & Francis Group, 2008.

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