Separation of Polymer Electrolyte Membrane Stack Components Using Sensor Integration for Non-destructive Disassembly

Dominik Goes(✉), David Kraus, Florian Kößler, and Jürgen Fleischer

KIT Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
dominik.goes@kit.edu

Abstract. Hydrogen technologies, such as polymer electrolyte membrane (PEM) electrolysis and fuel cells are considered the central and most promising technologies for the production and use of green hydrogen. End-of-life recycling is essential due to the presence of critical raw materials such as platinum group metals. Disassembly can improve the recycling outcome and enable other circular economy strategies such as reuse or remanufacturing of high value added components. The challenge in disassembling PEM stacks is to separate the stacked components non-destructively. This is due to the adhesion of the components to each other, as well as the low material thicknesses and component distances. The aim of this work is to identify suitable separation processes with a focus on mechanical processes. An industrial system concept will be developed and constructed. Sensors will be integrated into the system to enable accurate positioning of a cutting tool. Finally, the process is validated. The publication shows that non-destructive and automated separation of the individual components in PEM stacks using mechanical processes in combination with sensor-supported positioning enables the realisation of various circular economy strategies.

Keywords: Fuel Cell · Disassembly · Adhesion · Sensor integration

1 Introduction

1.1 Motivation

At the end of a product's life (EoL), different circular economy strategies can be pursued [1]: Recycling as a circular economy strategy involves the recovery of used materials. However, other strategies such as reuse and remanufacturing can retain the added value of an entire product or components. The prerequisite for reuse or remanufacturing of parts is a non-destructive extraction. The design of a PEM fuel cell stack is described in detail in [2]. Each stack is made up of up to hundreds of individual cells. Each cell features a bipolar plate (BPP), a membrane electrode assembly (MEA), followed by the next bipolar plate. There are

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different degradation mechanisms for the components. A typical cause of stack failure is perforation of the MEA [3]. The MEA or membrane is the component that limits the lifetime of the stack, whereas the BPP can have a longer lifetime. Regarding the cost structure, the main cost of the MEA is the cost of materials, whereas production costs predominate at BPP. [4]. Circular economy strategies can be derived from the duality between MEA and BPP in terms of degradation and cost structure: MEA needs to be recycled. Repair or remanufacturing should maintain the added value of BPP.

During operation, fuel cell stacks are exposed to conditions such as compression, acidic environments, overvoltage, temperature and humidity. After a stack has been used, BPP and MEA can adhere to each other in the sealing area and form a joint. In this area, the sealing material adheres to the polymer of the subgasket (e.g. polyethylene naphthalate) of the MEA. This adhesion, together with the low material thicknesses of the components (unshaped BPP around 100μm [5], laminated subgasket foils around 50μm [6]) of the components and the resulting small component distances (around 1mm or less) are the main challenges for disassembly. The causes and influencing factors (operating conditions see above) of adhesion have not yet been investigated. Tests such as peel and shear tests need to be carried out to evaluate the adhesive force. These analyses are not part of this work.

1.2 State of the Art

DIN/TS 54405 ([7]) specifies methods for separating and recovering adhesives and bonded parts from bonded component joints. A distinction is made between physical, chemical and mechanical methods. Chemical methods are not recommended due to the following reasons: (a) limited accessibility to the joint, (b) time consuming process, (c) damage to BPP or dissolving of catalyst from MEA not excluded, (d) possible contamination of BPP cooling channels. Aspects (a) and (d) can be justified by the structure of a stack and a BPP. Aspects (b) and (c) are process-related, as these methods usually result in the dissolution or decomposition of materials. Debonding by heating or freezing is a physical process. It can be used as an aid to debonding if the temperature limits are observed. Heating exceeds the sealant's glass transition temperature. Freezing embrittles the sealant. Both processes can lead to a reduction in adhesive force. Physical methods are not recommended for a repair scenario where only individual defined cells need to be separated. Targeted application to individual defined cells is difficult to achieve.

Non-destructive disassembly of PEM fuel cells has not been extensively studied in the literature. Component adhesion is also not addressed in the literature. The factors influencing adhesion have not yet been analysed. A solution for identifying the ideal position in relation to the Z-value (height) of the wedge is not proposed. In the literature, disassembly challenges have been identified and process chains elaborated ([8]), recycling strategies developed ([9]), manual disassembly procedures presented ([10]) and the need for automation highlighted ([11]). The patent landscape ([12–16]) provides more specific proposals for the disassembly of PEM fuel cells. The technical feasibility of the processes has not been demonstrated, there is no evidence of automation and some of the processes are destructive.

The state of the art shows that mechanical processes in particular are suitable for pursuing a variety of possible circular economy strategies. Furthermore, no automated solution has been proposed for the localisation of the joints and the positioning of a cutting tool. This work therefore focuses on the development of both, automated mechanical disassembly and localisation and positioning.

2 Materials and Methods

For reasons of availability and confidentiality, no commercial fuel cells can be used for the investigations and validations in this paper. Therefore, representative analogue components have been fabricated. The cell design is based on seven layer MEA and metallic BPP ([17]) including sealing with the following characteristics: Shaped and welded stainless steel foil (thickness 75µm, dimensions 219×117mm); bead sealing technology; screen printed elastomeric seal (width 1mm); flow field and manifolds. The investigations are not affected by the presence of CCM and GDL. Laminated subgasket foils (polyethylene naphthalate carrier film, 25µm thickness [6]) represent the MEA. A short stack consisting of alternately stacked laminated subgakset units and BPP was stacked and pressed (2,3MPa [18]). Adhesion in the sealing area occurred after a few weeks at room temperature and standard atmosphere in the compressed state.

3 Results and Discussion

Mechanical processes are suitable for disassembly, as described in Chap. 1.2. Different circular economy strategies can be achieved with mechanical processes. According to DIN/TS 54405, the options are peeling, cutting and stretching. Cutting is a possible solution in which the different circular economy strategies can be followed. One possible solution is cutting using a wedge as a separating tool. This process is analysed in detail below. A possible system design including sensor integration for position determination is described. The developed process is validated.

3.1 Construction of an Industrial System

An illustration of the system is shown in Fig. 1. The design includes two parallel linear axes with carriages. A load cell is mounted on the carriage of each axis. The axes are position controlled and are used to manipulate the cutting tool, in this case a knife-like steel wedge. Both axes can be driven synchronously or asynchronously. This means, that the angle of the cutting wedge around the Z axis can be varied. The lifting table is used to place and fix the fuel cell stack and is adjustable in height. Next to the lifting table, a laser triangulation line profile sensor is placed on its side so that it's measurement plane is perpendicular to the table surface. The fuel cell stack is placed on the lifting table with one of its short sides facing the profile sensor and the cutting wedge. Spring loaded anchor points, pneumatic cylinders or a vacuum clamping plate are all suitable for clamping the stack (not shown). An articulated arm robot with a suction gripper is integrated to handle the separated parts.

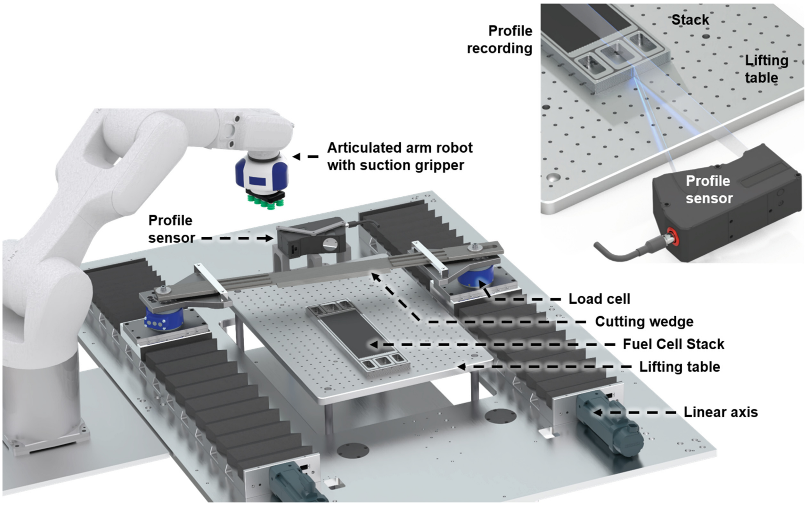

Fig. 1. Construction of the industrial system for disassembly of PEM fuel cells (left) with detailed view of the stack profiling setup (top right).

3.2 Separation Strategy and Parameters

To separate the top layer of the stack, the axes are driven so that the cutting wedge is inserted horizontally under this layer. To insert the wedge exactly between two layers and avoid collision with the stack, the height at which the wedge is moved must be precisely determined. This is achieved by using a profile sensor that detects the stack profile. This only demonstrates one of the options chosen for this system. The profile is analysed using a specially developed algorithm. Since the stack consists of periodically arranged layers the obtained profile also shows a pattern of recurring geometric features, i.e. the thin sides of the BPP, as the MEA doesn't tend to show up in the sensor profile due to its small width and transparency. An example profile is shown in Fig. 2. The setup for recording the profile is shown in Fig. 1. Notably each BPP is identifiable by it's two steep flanks. To identify the position of each BPP, the two flanks must be detected. The implemented algorithm achieves this by essentially calculating the second numerical derivative of the profile and finding inflection points. Since each BPP lies between two inflection points and always right of one rising and left of one falling inflection point, the position of each BPP can be calculated. The cutting position is then placed exactly between two plates. Minor features and noise in the profile are suppressed by only accepting inflection points correlating with sufficiently large slopes in the original profile.

The system operates in a closed information loop. First, the cutting wedge and lifting table are moved to their respective home positions. Then a measurement is taken by the profile sensor and the resulting profile is transferred to the custom evaluation software via an FTP server. There the cutting positions are determined using the above mentioned algorithm. The cutting coordinates are then sent back to the system control and the axes are driven accordingly in order to facilitate the cut. The separated layers can be removed manually or by an articulated arm robot. The process then starts again for the next layer.

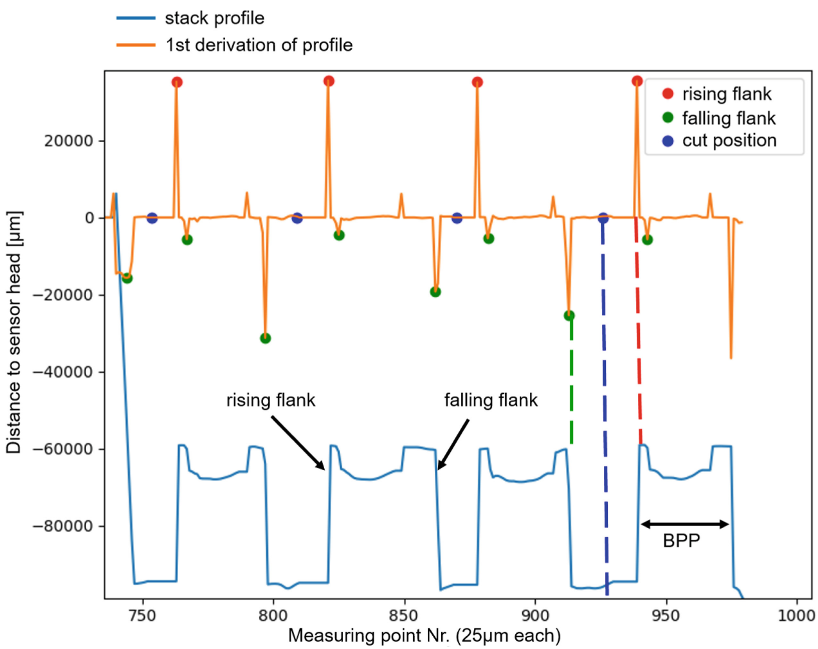

Fig. 2. The algorithm for analysing the cutting coordinates. The profile shows the cutting position between two BPPs. The MEA located between two BPPs cannot be seen on the profile.

3.3 Validation and Characterization

The analogue cells defined in Sect. 2 are used to validate the separation process. The validation test setup is shown in Fig. 3. The wedge can be set at different angles as it moves through the stack, allowing the influence of the cutting angle on the quality of the cut to be studied. By setting an angle, the cutting wedge is inserted over the corner of the stack rather than over the entire edge. This can simplify the insertion and eliminate height differences across the length of the stack in relation to the individual layers. The speed of the cutting movement can be adjusted to study the effect of cutting speed on the accuracy of the cut and the resulting damage patterns. Tests with the setup employing a cutting wedge with a continuous edge geometry at different cutting angles showed a good functionality of the algorithm described above. Out of twenty tests, only one profile showed an error in the detection of a BPP and did not lead to a correct cutting position. The requirement for the separation process is the non-destructive separation of the BPP. During disassembly, defects and damage can occur (see Table 1), which must be avoided.

Table 1. Failure patterns during separation process

Failure patterns	Cause	Measures
Edge deformation during insertion	Height differences over the length of the BPP	Insertion via corner instead of edge
Deformation of BPP corners	Algorithm errors	Algorithm optimisation
Deformation of BPP corners	Features in BPP corners (e.g. CVM connector or centring features)	Adaptation of cutting strategy or cutting wedge
Delamination of the seal or coating	Wedge thickness greater than cell distances	Acceptable
Damage to subgasket or delamination of GDL	Material thickness of the wedge greater than the distance between two cells	Acceptable

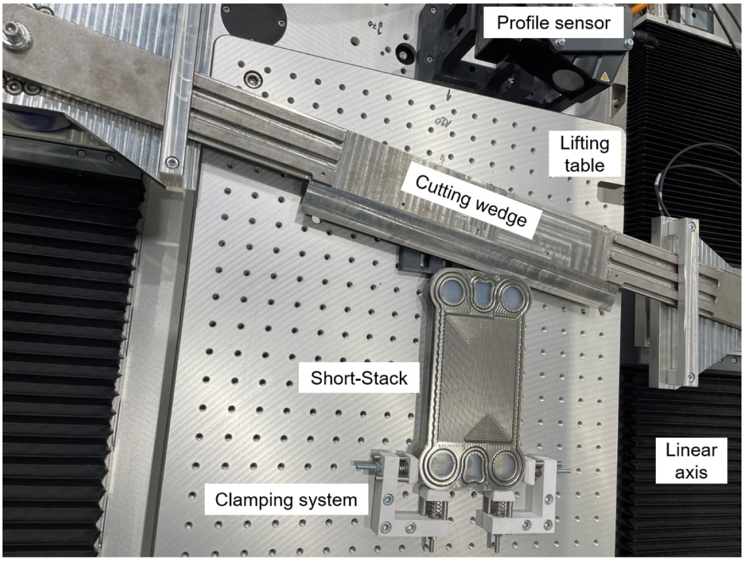

Fig. 3. Test setup for validation of the separation process with analogue short stack and angled wedge cutter.

3.4 Conclusion

Experiments using the setup as described in Sect. 3.1 showed the possibility of non-destructive disassembly of fuel cell stacks as BPP could be extracted undamaged. As the implemented process relies only on mechanical motion and force, and does not require any further thermal energy or material input, the process is energy and resource efficient. The implementation of a laser profile sensor enables the detection of cutting positions and promises to make the method transferable to other stack designs. Achieving undamaged disassembly is highly dependent on the geometry of the fuel cell stack and the cutting tool. Further research is required to improve the cutting geometry and tool response. There are several parameters that could be adjusted in future experiments to improve the results: (1) The geometry of the cutting wedge can be modified to avoid collision with small protruding geometric features; (2) The wedge could be agitated, e.g. by vibration or an ultrasonic pulse to further weaken adhesive bonds during cutting; (3) The stiffness of the wedge attachment could be reduced to allow small compensatory movement of the wedge; (4) A control loop could be implemented to monitor the cutting forces and adjust the cutting movement accordingly.

Other possible disassembly processes, such as peeling or alternative cutting processes, as well as the use of physical processes to reduce the adhesive force, must also be analysed. The adhesive force needs to be quantified and the factors influencing adhesion analysed. The process developed must be profitable in terms of cost and process time. These values cannot be quantified at present. The system is a proof of concept and needs to be optimised in terms of process time.

The automated system currently competes with manual disassembly because there is no proven process.

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