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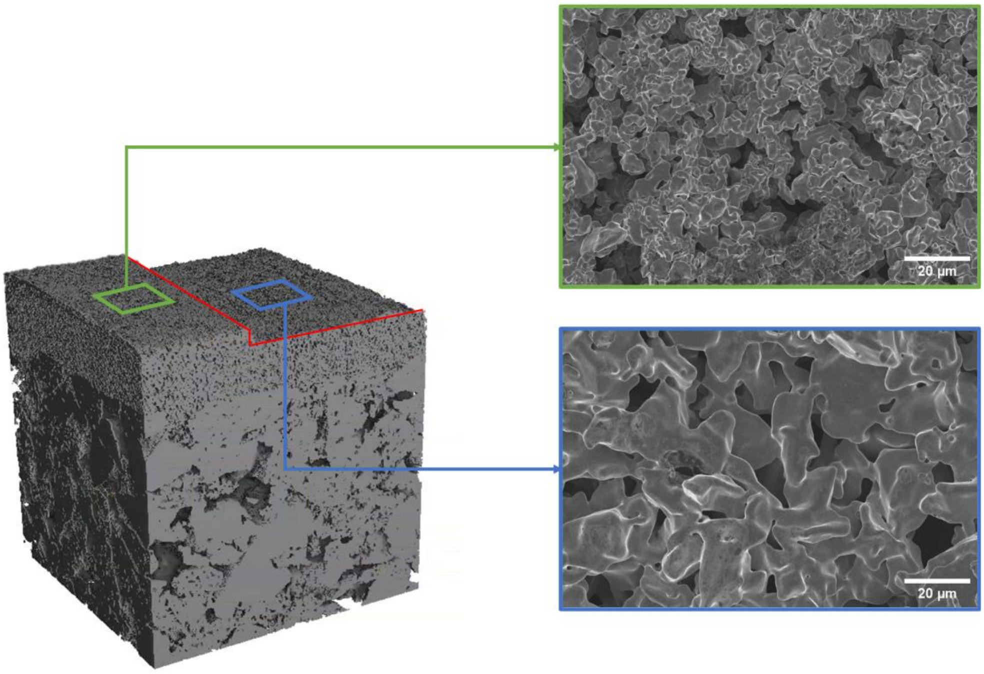
Final report from 10 December 2024

PTLs for PEM Electrolysis

Multilayer NovElyTi Porous Transport Layers for Polymer Electrolyte Water Electrolysis (PEWE)



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Zusammenfassung

Für die Polymer-Elektrolyt-Wasserelektrolyse (PEWE) ist an Anode (Sauerstoffentwicklung) aufgrund der hohen Potenziale (> 1,5 V) ein elektrochemisch stabiles, poröses Material erforderlich. Heute werden für diesen Zweck poröse Titanstrukturen eingesetzt. In einem früheren, vom BFE finanzierten Projekt wurden poröse Titan-Transportmaterialien (NovElyTi-Materialien) für die PEWE entwickelt, die derzeit in Lizenzverhandlungen mit internationalen Partnern stehen. Die glatten Oberflächen der NovElyTi-Materialien sind ein ideales Basismaterialien für die Weiterentwicklung von Materialien, die eine hohe Katalysator-Nutzung auch bei niedrigen IrO2-Beladungen ermöglichen.

Heute bestehen NovElyTi-Materialien aus zwei Schichten: einer Trägerschicht und einer mikroporösen Schicht. Das vorliegende Projekt beschäftigt sich daher mit der Weiterentwicklung dieser Zweischichtstrukturen hin zu Multischichtmaterialien, die den Einsatz von sehr geringen IrO2-Beladungen ermöglichen.

Dieser Projektbericht beschreibt die Herstellung und Charakterisierung von 3- Materialien mit nochmals feinerer Oberfläche, er beschreibt die Resultate welche mit einem neuen Katalysator, der optimiert für tiefe Beladungen ist, und der letzte Teil beschäftigt sich mit einem neuen Konzept, bei dem TiN anstelle einer PGM-Schicht verwendet wird, um den Kontaktwiderstand zwischen der Katalysatorschicht und der porösen Transportschicht zu verringern.

Summary

For polymer electrolyte water electrolysis (PEWE), at the anode, due to the high potentials (> 1.5 V), an electrochemically stable porous material is required. Today, porous titanium structures are applied for this purpose. In a previous BFE-financed project, titanium porous transport materials (NovElyTi materials) have been developed for PEWE which today are discussed for licensing with international partners. The smooth surface NovElyTi materials are expected to serve as ideal base materials for the further development of materials that offer high catalyst utilization also at low IrO_2 loadings.

Today, NovElyTi materials consist of two layers: a support base layer and a microporous layer. Therefore, this project is about the further development of two-layer structures into multilayer materials, allowing the use of very low loadings of IrO_2 in the adjoint catalyst layer.

This report describes the fabrication and the characterization of the materials and shows that indeed the 3rd layer improves catalyst utilization. Further the evaluation of a new catalyst, optimized for low loadings is described, while the last part is about a new concept using TiN instead of a PGM layer to reduce the contact resistance between the catalyst layer and the porous transport layer.

Main findings

1. PSI now can prepare in-house (with automated spray technique & sintering), titanium porous transport layers for PEWE that have a very fine (5 um particle size) surface layer.
2. It is shown that when using these materials in PEWE cells (at a loading of 0.5 $mg_{Ir}cm^{-2}$ IrO_2), the catalyst utilization is higher and performance better than with the standard materials.

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Abbreviations

CL	Catalyst Layer
CCM	Catalyst Coated Membrane
MPL	Micro Porous Layer
PEWE	Polymer electrolyte water electrolyzer
PGM	Platinum Group Metals
PTL	Porous Transport Layer
SEM	Scanning Electron Microscopy
XTM	X-Ray Tomographic Microscopy

1 Introduction

1.1 Background information and current situation

The use of expensive catalysts such as iridium oxides and platinum for the oxygen and hydrogen evolution reactions in polymer electrolyte water electrolysis (PEWE) leads to high production costs. To overcome this issue, one of the goals is to reduce catalyst loading or the use of non-noble metal catalysts [1]. Therefore, the elucidation of the relevant design of the anodic porous transport layer (PTL) for high catalyst utilization is a key requirement in the field of PEWE. In fact, besides defining the interface to the catalyst layer (CL), PTLs are a crucial component of PEWE that can optimize the transport of reactants and products to/from the CL, including electrons, heat, water, and oxygen.

Good interfacial contact between the catalyst layer and the PTL interface is necessary to achieve high catalyst utilization. Recent studies revealed that the structure PTL and the catalyst layer is a crucial factor that limits cell efficiency and contributes significantly to CL performance and use of the catalyst [2]. Therefore, two-layer PTL/MPL NovElyTi materials for PEWE have initially been developed in a former BFE project. The two-layer structures allowed one to improve the anode catalyst utilization for conventional IrO_2 loadings and are about to be commercialized by licensing the patents to international companies.

In a pursuit of low catalyst loading and high catalyst utilization, one should not forget about catalyst layer morphology. Since, while decreasing catalyst loading without altering the catalyst support inevitably produces thinner CLs and challenges to sustain the connectivity in the CL and affect interface resistance. First, this could be done by reduction of the packing density of the catalyst using a catalyst support material [3]. Heraeus (Germany) recently developed a new type of supported OER catalyst with a reduced iridium weight percentage (10 – 45 wt%) on a TiO_2 support, which allows lower packing densities. However, TiO_2 is a wide-bandgap semiconductor with poor electronic conductivity, and still it is important to be able to prepare well conducting catalyst layers at low catalyst loadings. Otherwise, to achieve low CL/PTL contact resistance and increase electronic conductivity, a highly conducting catalyst layer such as Pt coating on a PTL can be used. However, to significantly contribute to the commercial viability of low-cost hydrogen production technologies, replacement for this traditional Pt coating needs to be considered.

1.2 Purpose of the project

The coarse structure PTL can develop inactive zones of the catalyst layer, which occurs when the catalyst layer is not contacted to the titanium structure. The situation becomes worse when the IrO_2 catalyst loading is reduced, and the catalyst layers become thinner. Therefore, the purpose of this work is to explore and optimize the design of titanium-based porous transport layers (PTLs) for PEWEs. By developing a PTL structure with even finer surface characteristics, this is done here by modifying the existing titanium 2-layer structures with a 3^{rd} very fine top layer. At PSI, before this project, no Titanium structures have been prepared and sintered. Further the study seeks to improve the efficiency of catalyst utilization and reduce contact resistance between Ti structures with low IrO_2 loadings.

1.3 Objectives

The primary objective of this research is to investigate and develop surface optimized multilayer titanium based porous transport layer (PTL) structure for PEWE. The study focuses on improving the surface of existing NovElyTi materials and further improving the electrochemical performance of through the implementation of the third and finer Ti-powder layer design. This includes coating of Ti powder-based ink and sintering process, as well as evaluating the effects of sintering conditions, binder mass fractions, and ink composition on the final structure.

The electrochemical performance of these new 3-layer materials is assessed in 4 cm2 cells. With the measured mass-activity of the catalyst as a main evaluator. Higher mass activities mean that the apparent kinetics of the catalyst are improved through improving the contacting and/or mass transport.

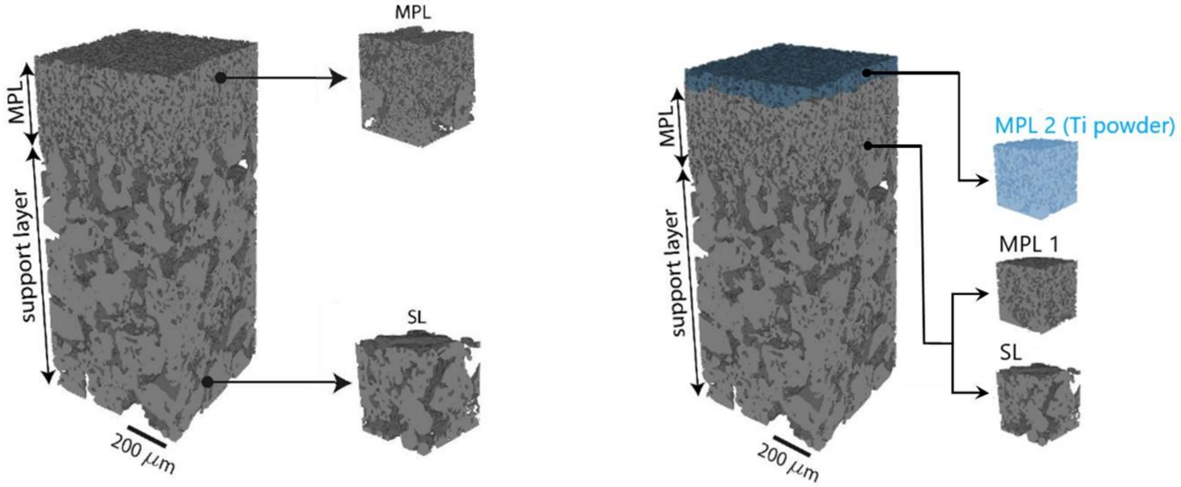


Figure 1: NovElyTi 1 sintered 2-layer PTL (left) and aimed multilayer 3-Layer PTL (right)

Additionally, the project aims to assess the impact of catalyst layer (CL) thickness, and the use of conductive coatings on reduction contact resistance between Ti structures with low IrO_2 loadings. The goal is to optimize catalyst utilization while maintaining low catalyst loading for efficient PEWE performance. This involves physicochemical characterization of the samples, analysing electrochemical behaviors via polarization curves and impedance spectroscopy.

2 Procedures and methodology

2.1 Fabrication of the components

2.1.1 3-layer MPL fabrication.

Ti ink was prepared by mixing Ti powder in a particle size of 5 µm, PVA as a binder, ethanol/water as a solvent and spray-coated using an automated programmable coating system on existing MPL and then sintered in the vacuum furnace to obtain 3-layer MPL. Binder and residual solvent were removed under flowing Ar, maintaining an average pressure of 15 mbar in the furnace chamber. The samples were heated at 2 K min^{-1} to 500 °C, followed by 30 minutes of waiting. Then Ar was removed to create vacuum and heated again 2 K min^{-1} to 800 °C, following 2 h of waiting time.

2.1.2 Catalyst Coated Membrane (CCM) fabrication.

The CCMs were manufactured by preparation of catalyst ink and spray coating using an automated programmable coating system on the membrane (Nafion 115, 127 µm thickness) to obtain 0.5 mg$_{Ir}$cm^{-2} in the anode and 0.5 mg$_{Pt}$ cm^{-2} at the cathode. For the cathode CL, commercial Pt/C (TEC10E50E, Tanaka Kikinzoku Kogyo) was used. For the anode CL, Umicore at 75 wt.% IrO_2@TiO_2 was used. Furthermore, to study a balance between catalyst loading and in-plane conductivity, a reduced iridium weight percentage on a TiO_2 support was used, particularly commercial catalyst Heraeus at 45, 30 and 10 wt.% Ir (H2-EL-xxIrO-S).

2.1.3 Conductive layer fabrication.

Vacuum plasma spraying (VPS) technology was used to apply 150 nm TiN and 40 nm Pt on the surface of MPLs.

2.2 Physicochemical characterization

2.2.1 Imaging Techniques

Scanning electron microscopy (SEM) is a fast, powerful imaging technique to investigate the surface morphology of spray-coated titanium powder before and after sintering in the oven. It is also used to identify the structural difference of different types of Ti powders. Additionally, cross-sectional SEM can provide information on the uniformity of the CL deposition and thickness. In terms of PTL, SEM is helpful for visualizing the surface morphology of CL and PTL.

X-Ray computed tomography (XTM) has a lower resolution than SEM but can probe not only surface properties but also 3D structural information down to a micrometer resolution. The in-house available lab-CT can operate with a voxel size of below 2 μm, that is sufficient to measure PTL/2MPL structures. The information is used to analyse the inner structural changes of PTL/2MPL after sintering, as well as to analyze the thickness and homogeneity distribution of the deposited surface.

2.2.2 Electrical Conductivity Measurements

Through plane conductivity of catalyst powder. To measure the ex-situ electrical conductivity of each catalyst powder, impedance spectroscopy measurements were performed. The catalyst powders were kept under a constant pressure of 0.6 MPa for 5 min, and the electrical resistivity was evaluated by four-wire impedance spectroscopy measurements at room temperature applying a bias of 15 mV in the frequency range between 0.50 MHz and 20 kHz. With the though-plane mode, the electrical conductivity (σ_{TP}) is calculated via equation (1).

$$\sigma_{TP} = \frac{d}{A \times R} \tag{1}$$

where, d represents the thickness of the powder inside the chamber, A is an electrode area, R is a measured electrical resistivity, $\sigma_{TP}$is a through-plane conductivity in $S.cm^{-1}$.

In-plane conductivity of catalyst layer. To measure in-plane conductivity of the catalyst layers, catalyst ink was spray coated on the Teflon sheet and placed on the 4 – electrode cell, with 10 mm as the distance between the two internal electrodes. The electrical resistivity of the catalyst layers was calculated using measured potential (V) at 0.001 A of current. The in-plane electrical conductivity (σ_{IP}) is given by equation (2).

$$\sigma_{IP} = \frac{L \times I}{d \times W \times U} \tag{2}$$

where, L is 10 mm the distance between the 2 internal electrodes, d is the thickness of the catalyst layer sample, W is the width of the catalyst layer sample, I represent the measured current, σ_{IP} in-plane electrical conductivity in $S.cm^{-1}$.

2.3 Electrochemical Characterization

Electrochemical characterization was carried out on the electrolysis test bench. Electrochemical performance evaluation was performed by recording polarization curves and high-frequency resistance

(HFR) measurements and a Tafel analysis The cells were conditioned at 5 bars in $N_2(g)/H_2O(l)$ for at least 12 h and the leakage rate was controlled during this time. After this, a potentiostatic break-in cycle protocol (2.0 V – 2.6 V, 50 °C, 10 bar) was followed. The measurements were started when stable performance and HFR were reached (ΔHFR < 0.1 mΩ cm^2 min^{-1}). Polarization curves were recorded in a current density range between 0.001 and 5 A cm^{-2} in galvanostatic mode with holding times of 10 s for each current density step. The holding time was chosen based on the work of Suermann et al. [4] who showed that 10 s is an optimal compromise between thermal equilibrium and hydrogen crossover at low current density. The HFR was measured at each step at 25 kHz for 1 s. All polarization curves were recorded at 10, 5, and at 1 bar and 50 ° C and 80 °C, respectively. Each measurement was repeated at least three times for each combination of materials, temperature, and pressure. For selected material combinations, two or three-cell repeats were performed to confirm the results and check the reproducibility in the measurements.

3 Results and discussion

This section is arranged with 3 subsections on the result of the project.

3.1 Fabrication and Optimization of Three-layer PTL/MPL

To improve the surface characteristics of titanium PTLs, a third and finer titanium layer approach was developed. This innovative approach was challenging as PSI had limited experience with the sintering of porous titanium structures. In the first part of the project development of the third and fine layer was done by air-brushing technique. Furthermore, the sintering process and effect of titanium ink composition on a final structure was studied. For that, sponge, spherical and HDH, in 5, 6 and 10 um (but in average 1-3 um) Ti powders were purchased. Figure 2a shows SEM images of the Ti powders used, where the structural differences can be seen. Figure 2b shows the SEM images of the surface of hand-sprayed 3-layer PTLs after sintering at 1000 ° C and structural differences depending on the Ti powders (blue rectangle), binder mass fraction (orange rectangle) and positioning (green rectangle), are shown and it can be seen that:

- Difference of Ti powders: the raw Ti powder impacts the final structure of deposition and 3rd Ti-powder layer.
- Fractional mass of binder: higher mass fraction of the binder creates a more porous structured Ti layer (comparing 40 wt% to 10 wt.% PVA).
- Positioning during sintering impacts the final structure of the Ti-layer.

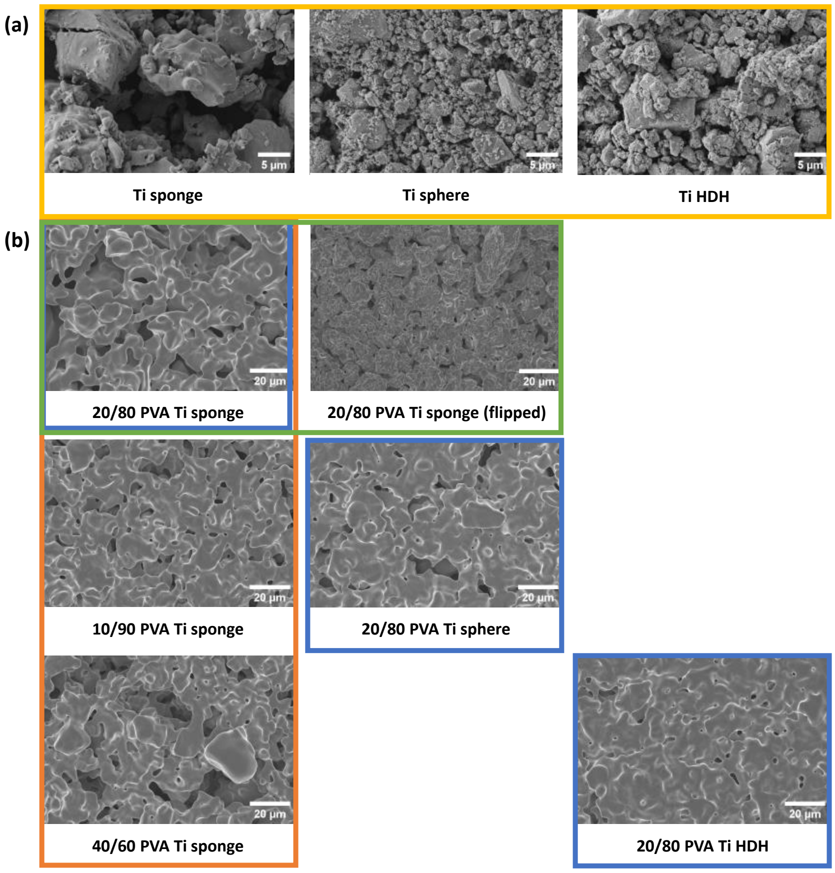


Figure 2: SEM images of (a) Ti powders with the magnification of 2500 × (sponge, sphere, HDH, from left to right, (scale bars 5 µm) and (b) 3-layer PTL surface (manually airbrushed samples) after sintering at 1000°C with the magnification of 800 × (scale bars 10 µm).

During this study deformation of PTLs after sintering at 1000° C was observed. Therefore, the sintering temperature was optimized (see Chapter 2.1.1) and the Ti powder ink coating process was changed to automatic spraying during 2024, very reproducible samples were produced. These samples were morphologically characterized using XTM and SEM, and electrochemically tested.

3.1.1 SEM

Figure 3 shows the SEM images of the surface of the 2-layer and the developed, automatically sprayed, 3-layer PTLs. The structural differences and finer surfaces of MPLs are clearly visible. The top layer of the 2-layer structure has a particle size of 15 um and the particle size of the 3-layer, shown in Figure 1b is 5 um. The typical thickness of the automated sprayed layer is 10 – 20 um.

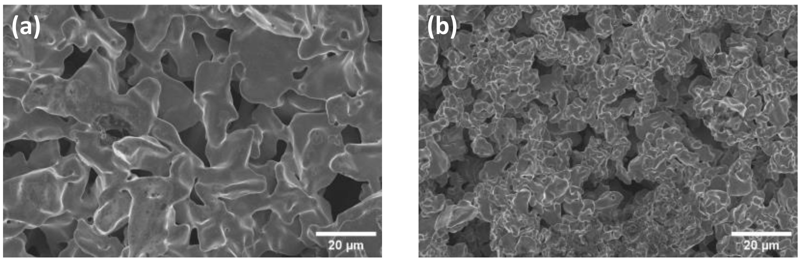
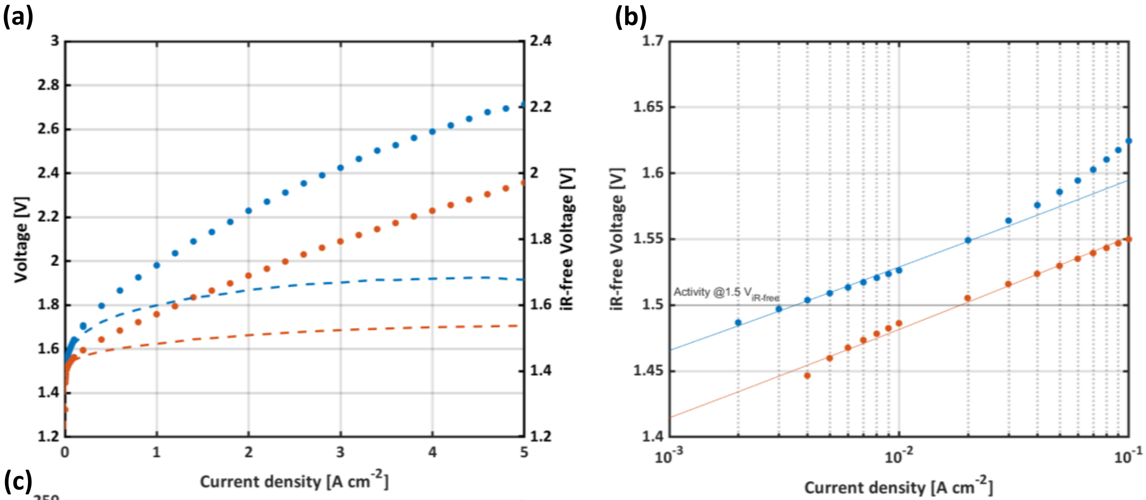


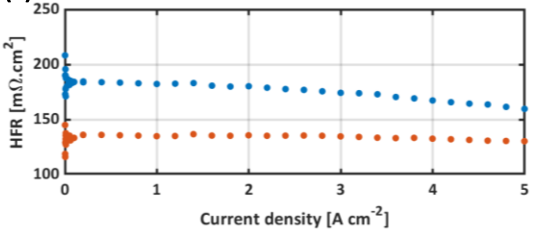
Figure 3: Surface structure of PTLs (a) 2-layer with 15 um and (b) a 3-layer with sponge in particle size of 5 um (scale bars 20 µm).

3.1.2 Electrochemical results

The electrochemical performance of the developed 3-layer MPLs was evaluated through polarization curves and impedance measurements (Figure 4). The results show a significant increase in catalyst utilization with the 3rd additional finer MPL layer, at a catalyst loading of 0.5 mg_{Ir} cm^{-2}. The 3-layer PTL thus shows the potential of these materials with modified surface to enhance electrolyzer efficiency at reasonably low loading of the precious metal catalyst.

Recent evidence also showed that MPLs have lower hydrogen crossover rates [5]. Therefore, to study 3-layer MPL effect on hydrogen crossover, a collaboration with National Renewable Energy Laboratory (NREL, Colorado, USA) is being discussed to perform such measurements.





(d) Sample	Tafel slope (mV.dec^{-1})	$i_{@1.5V}$ (mA.cm^{-2})	mass activity (A/g)
2 – Layer PTL	72	4	8
3 – Layer PTL	70	20	40

Figure 4: Electrochemical performances of PEWE cells with different anodic PTL surface structure: (a) polarization curve in point lines and iR-free polarization curve in dashed lines, (b) zoom into low current density region (Tafel regime), (c) HFR measurements, and (d) table of kinetic data for all MPLs with different coating (0.5 $mg_{Ir}cm^{-2}$, N115, T = 80 ° C, balanced pressure of 10 bar).

3.2 Effect of CL thickness

In pursuit of low loading CL and high utilization of the catalyst, one should not forget about connectivity in the CL. Indeed, decreasing catalyst loading without altering the catalyst support inevitably produces thinner CLs [6,7], and at a given point (corresponding to CL thicknesses below ≈ 2 µm) it is challenging to sustain the connectivity. Therefore, also the CL thickness effect on PEWE performance was studied in the presence of an MPL. For that purpose, reduced iridium weight percentage (10 – 45 wt%) on a TiO_2 support catalyst by Heraeus (Germany) was used to prepare CLs with different morphology and physicochemical properties. During this study 2-layer PTL with Pt conductive layer was used. Top layer was coated with a thin (≈ 40 nm) Pt-layer corresponding to a loading of ≈ 0.08 $mg_{Pt}\ cm^{-2}$. The coating was done in-house (TIPSI, PSI) by magnetron sputtering with argon as a sputtering gas.

3.2.1 Physicochemical characterization

Figure 5 represents physicochemical difference of 4 different CLs, prepared with 4 different catalysts: Umicore 75 wt.% Ir, Heraeus 45, 30 and 10 wt.% Ir, (U75, H45, H30 and H10, respectively). Electrical conductivity of the catalyst powder and the catalyst layer are represented in Figure 5a. Unfortunately, electrical conductivity of CLs prepared using H30 and H10 could not be measured. Nevertheless, the findings indicate that lowering the packing density of $IrO_2@TiO_2$ increases the thickness of the CL and its electrical conductivity, given that TiO_2 is a wide bandgap semiconductor with low electronic conductivity, conductivity is given by the Ir/IrO_2 shells.

The catalyst layers prepared with different catalyst powders were visualized by SEM images, and their thicknesses were measured via cross-sectional analysis of the SEM images. **Error! Reference source not found.**b (top) unveils the surface morphology and (bottom) cross section of the CLs prepared with the catalyst with different Ir packing density. The cross-sectional images show the logical evolution of catalyst layer thickness with increasing catalyst/support ratio. Measured CL thickness from the cross-sectional images is represented in Figure 5a with blue lines. The change of the catalyst/support ratio significantly changes the thickness of the catalyst layer. This means that low loadings, still relevant CL thicknesses are obtained for the 10 and 30% percent samples, however with decreased intrinsic electrical conductivity.

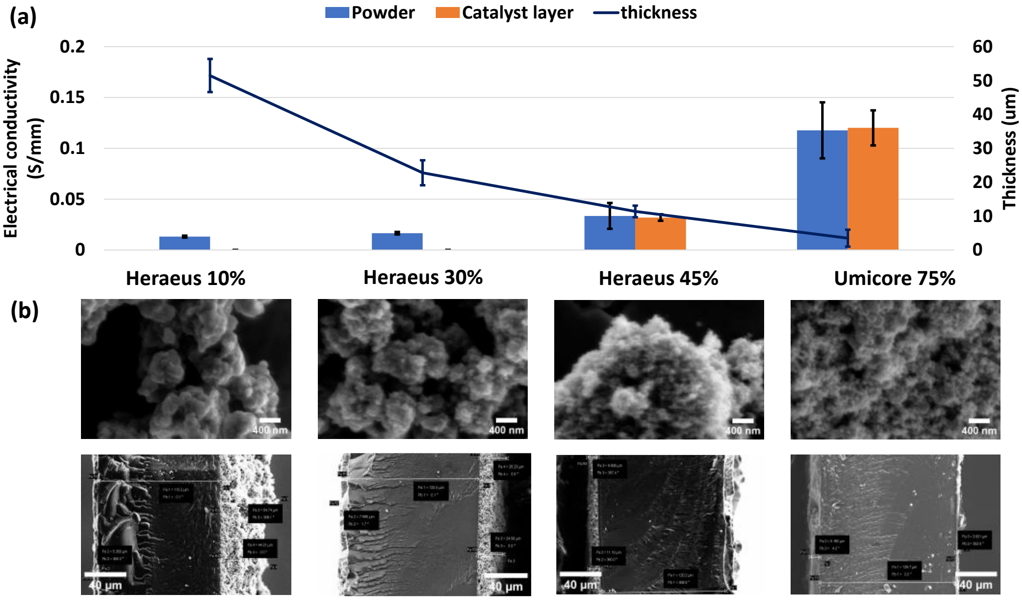
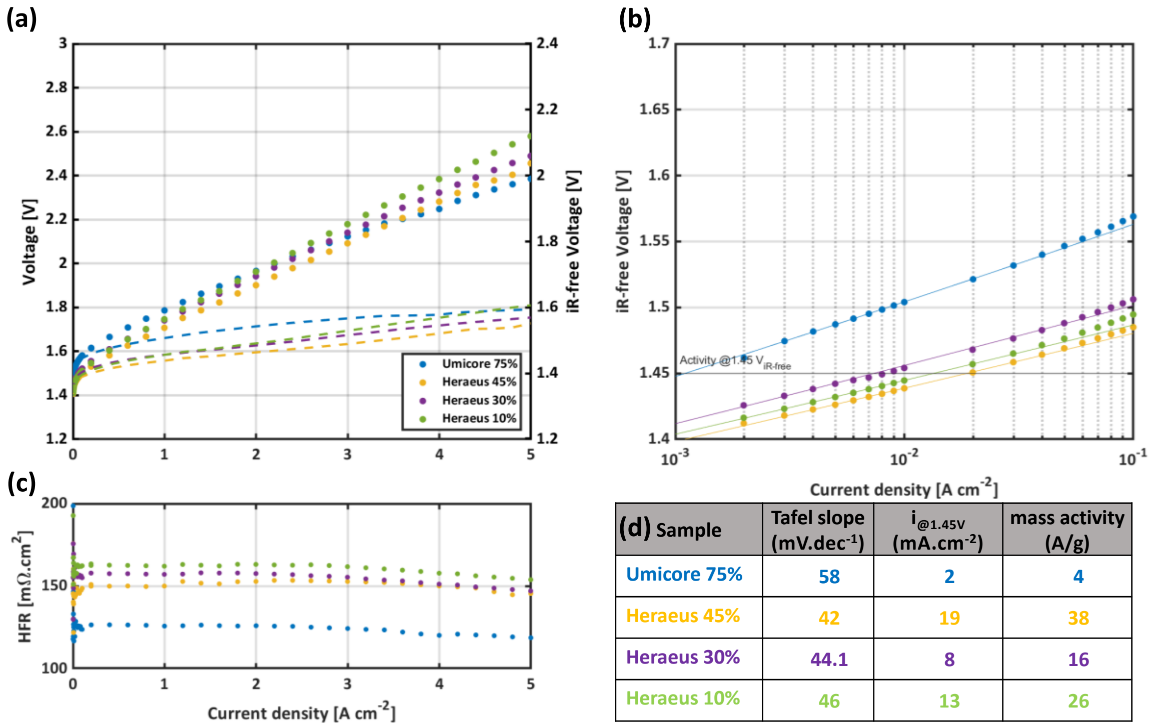


Figure 5: Physicochemical characterization: (a) electrical conductivity of catalyst powders (in blue) and catalyst layer (in orange), (b) SEM images of all catalyst (top) with magnification 500 X times (40 µm), and cross-sectional images of catalyst layers (bottom) with magnification 25 kX times (400 nm, from the left to the right: Pt/C catalyst layers with 0.5 $mg_{Ir}cm^{-2}$, membrane and IrO_2@TiO_2 catalyst layer).

3.2.2 Electrochemical results

Figure 6 represents the electrochemical performance results of CCMs prepared with the different catalysts Heraeus at 45, 30 and 10 wt.% Ir and Umicore 75 wt.%. The conductivity of the CL is given by the IrO_2 forming a core-shell structure around the TiO_2 particles, which plays a critical role in the high frequency resistance (HFR, Figure 6c). However, comparing the mass activity of the catalyst layer in Figure 6d, it shows that the thicker CLs have the expected improved values, though at the line at the expense of the increased HFR.



(d) Sample	Tafel slope (mV.dec^{-1})	$i_{@1.45V}$ (mA.cm^{-2})	mass activity (A/g)
Umicore 75%	58	2	4
Heraeus 45%	42	19	38
Heraeus 30%	44.1	8	16
Heraeus 10%	46	13	26

Figure 6: Anode catalyst layers with Pt coated 2-layer PTL for PEWE (0.5 mg$_{Ir}$cm^{-2}): (a) polarization curves in point lines and iR-free polarization curve in dashed lines, (b) zoom into low current density region (Tafel regime), (c) HFR measurements (N115, T = 80 ° C, balanced pressure of 10 bar) (d) table of Kinetic data for all measured cells.

Figure 7a represents the influence of the anode CL type and thickness on HFR of the entire cell. The HFR does reflect the membrane ionic resistance and the CL electrical conductivity. However, considering that the same membrane and the same ionomer content in the CL were used, we can link the change in HFR with the electrical CL conductivity. Figure 7b shows the evolution of ex-situ measured in-plane conductivity compared to the corresponding HFR value. It is feasible that the difference in HFR is due to a difference of CL conductivity. This finding is supported with results from other research groups [8].

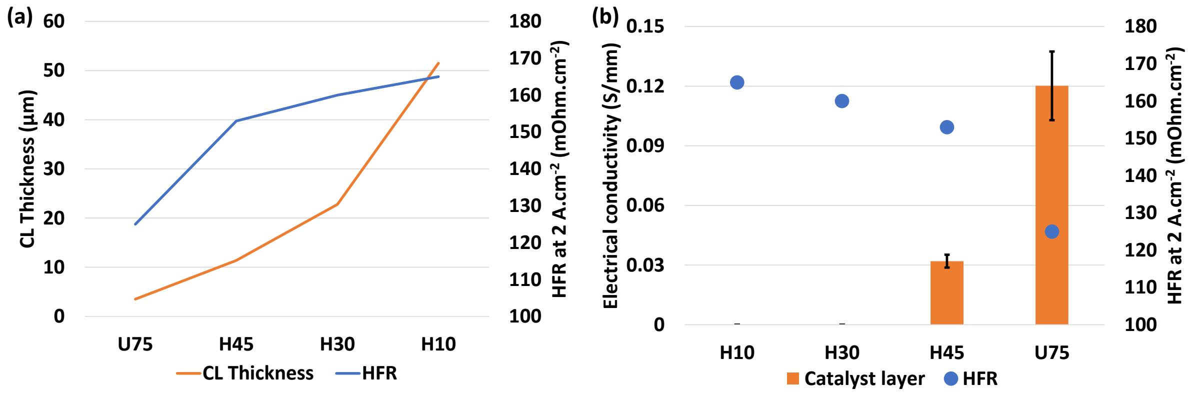
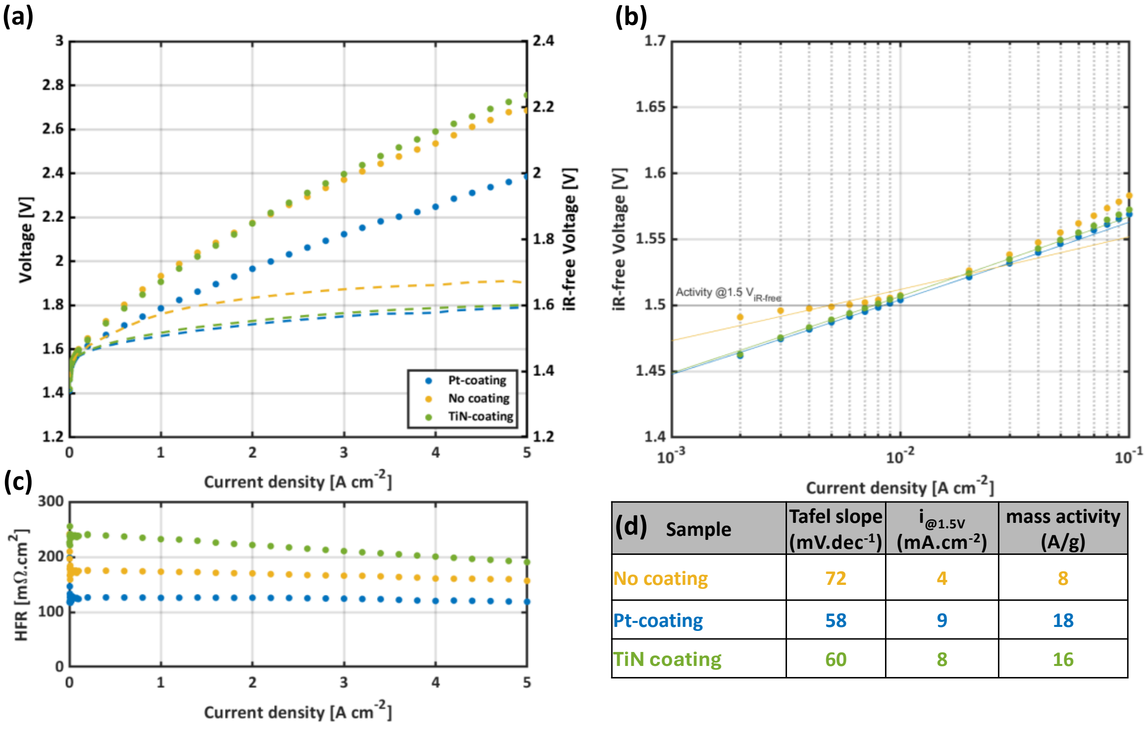


Figure 7: (a) anodic CL thickness (µm) and cell HFR, (b) CL electrical conductivity (S mm^{-1}) and HFR at 2 A cm^{-2} of the different catalysts

3.3 TiN layer

There is another important point which one should consider while pursuing low loading CL: at low catalyst loadings, unconnected parts CL can affect interface resistance. To achieve low CL/PTL contact resistance and increase electronic conductivity, a highly conducting catalyst layer or a Pt coating on a PTL is state of the art [3,9]. Therefore, an attempt to replace the protective Pt coating on the PTL by a TiN layer on top of existing 2-layer structure was made. Top layer was coated with a thin 150 nm TiN layer.

In Figure 8 the electrochemical performance of TiN-coated PTL is compared to a Pt coated and an uncoated PTL. Interestingly, the results of the TiN-coated PTL overlap with the result of uncoated PTL, which is assumed to be probably due to the lower electrical conductivity of TiN (2.5 10^6 S m^{-1}) ~4 times lower than that of Pt (9.52 10^6 S/m) and is remarked from the difference of HFR. Moreover, the iR-corrected performance of the TiN sample overlaps with that of the Pt-coated PTL. This is an interesting observation and means that Pt-utilization is enhanced but an additional resistance introduced and calls for further study of different thicknesses of TiN coatings.



(d) Sample	Tafel slope (mV.dec^{-1})	$i_{@1.5V}$ (mA.cm^{-2})	mass activity (A/g)
No coating	72	4	8
Pt-coating	58	9	18
TiN coating	60	8	16

Figure 8: Electrochemical performances of TiN, Pt and uncoated PTL/MPLs for PEWE: (a) polarization curve in point lines and iR-free polarization curve in dashed lines, (b) zoom into low current density region (Tafel regime), (c) HFR measurements, and (d) table of kinetic data for all MPLs (0.5 $mg_{Ir}cm^{-2}$, N115, T = 80 ° C, balanced pressure of 10 bar).

4 Conclusions

This project is about the further development of 2-layer structured porous transport layers into multilayers allowing the use of low loadings catalyst layers and dealing with the challenges it might bring. In the first part of the project in 2023, 3-layer PTL with a fine Ti top-layer on existing two-layer materials using airbrushing techniques was developed. The concept of 3-layer PTL was proven but there was room for improvement in reproducibility and further morphological and electrochemical characterization. The second part of the project, in 2024, we improved the reproducibility using an automated programmable coating system and following optimized sintering procedure. The study demonstrated that a third and finer titanium layer on the top of the PTL structure significantly enhances catalyst utilization, reduces contact resistance, and improves the overall electrochemical performance at low catalyst loading (0.5 $mg_{Ir}cm^{-2}$).

Furthermore, the investigation into the effects of catalyst layer thickness, and conductive coating layer (e.g., Pt and TiN) revealed insights into the trade-offs between catalyst performance, conductivity, and layer integrity. Lowering the ratio of support/catalyst increases the thickness of the CL but also the HFR due to lower electrical conductivity of the catalyst material. Moreover, the use of TiN as a conductive layer show promise for improving the overall performance without the use of the traditional platinum coatings on PTLs, though further optimization is needed to balance conductivity and resistance.

5 Outlook and next steps

Summarizing the result of current project, it was confirmed that the multilayer PTL structure enhances the anodic catalyst utilization in PEWE. Future work should focus on refining these multilayer PTLs and integrate them into porous transport electrodes (PTE) and further minimizing catalyst loading. Additionally, durability studies could be pursued to reinforce the feasibility of the durability and cost efficiency of PEWE. Furthermore, based on this work:

1. An Ambizione project (SNF) has been submitted.
2. Some samples of the 3-layer PTL is about to be sold to a Swedish company.
3. H_2 crossover measurements at NREL (USA) of 3-layer PTLs are initiated.
4. Coating of Pt layer between MPLs, as a potential recombination catalyst and study of the effects on the H_2 crossover compared to catalyst incorporation in the membrane is initiated.

6 National and international cooperation

6.1 International Cooperation

Collaboration to study H_2 crossover at the National Renewable Energy Laboratory (NREL, USA) for next year are initiated at the time.

7 Publications

Two publications are in progress and will be published in 2025.

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