FIT-4-AMANDA

Future European Fuel Cell Technology: Fit for Automatic Manufacturing and Assembly

EUROPEAN COMMISSION
Horizon 2020 | FCH-01-1-2016 | Manufacturing technologies for PEMFC stack components and stacks
GA # 735606

Deliverable No.	Fit-4-AMandA D5.6	
Deliverable Title	Public report on Comparison of the implemented methods to their standard lab-based counterparts	
Deliverable Date	2020-08-31 (according amended GA # 735606)	
Deliverable Type	Report	
Dissemination level	Public (PU)	
Written By	Martin Biak (TUC)	August 2019 – January 2021
Checked by	Thomas Wannemacher (PM) Anna Molinari (UNR)	2021-01-20 2021-02-21
Approved by	Thomas Wannemacher (PM) Anna Molinari (UNR)	2021-01-21 2021-02-21
Status	Final	2021-01-22

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1 Publishable Executive Summary

The main objective of the project Fit-4-AMandA[1] is to build a mass-manufacturing machine (MMM), which includes inline quality control (QC) using a non-destructive testing (NDT) and which is capable of ramping up the production of the polymer-electrolyte membrane fuel-cell (PEMFC) stacks. Although there is no real so-called off-the-shelf solution, the QC of the PEMFC stack's repeating parts such as bipolar plates (BPPs) and membrane-electrode-assemblies (MEAs) gained much attention by the fuel cell community in the recent years.

This report summarises the efforts to provide a concise overview of the QC methods suitable for BPPs, MEAs or catalyst coated membranes (CCMs) as investigated in the scope of WP5. It describes the road from lab-scale versions of QC methods to the large-scale implementation, which in the end will be suitable for implementation into the MMM.

Because of the measurement and quality-assurance (QA) tasks differ greatly, a variety of different measurement methodology approaches had to be taken into account. For this purpose, various technologies from different technology providers and measuring device manufacturers were identified, investigated with regard to their suitability for the specific measurement task and evaluated. It turned out that this task is not trivial. Not only there is no so-called off-the-self solution, but, in some cases, there are no suitable measuring technologies available on the market. Thus, compromises had to be made with regard to measuring accuracy or measuring time.

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[1] Future European Fuel Cell Technology: Fit for Automatic Manufacturing and Assembly – Fit-4-AMandA (EU project, duration 01 Mar 2017 – 31 Dec 2020, 45 months). Funding Programme H2020-JTI-FCH-2016-1, Grant Agreement #735606.

2 Introduction

In order to keep a scrap amount at the minimum level, a development of a PEMFC production line needs to go hand in hand with an advancement in the quality control. At the low production volumes (hundreds of PEMFC stacks), a QC testing does not necessitate high frequencies, i.e., a fast run-through of the QC tests. The more the production volumes are increased, the more needs to be QC methods accelerated to avoid creating a bottleneck in the production. When the production reaches a plateau, because the offline QC cannot match the production speed, a transition to the inline QC is necessary to further increase the volume of the production and simultaneously keeping the quality of the end product at the same level.

In the scope of the project Fit-4-AMandA, an MMM with an automation grade of more than 90 % was developed capable of producing PEMFC stacks in one assembly line at a theoretical volume of more than 10,000 stacks/year (see Table 1)[1;2]. To reach this target, the MMM needs to produce one PEMFC stack every 30 minutes. Assuming Proton Motor's PM400 PEMFC stack format with an exemplary number of 96 cells, the cycle time of 18 seconds per cell is required in the MMM. This leaves only a short time for the QC. Since the PEMFC stack in MMM is built by alternating two subassemblies BPP and MEA, on average requires MMM one subassembly every 9 seconds. In the confidential report D5.1, it was already established that the QC will be performed on the FC parts as they are entering the MMM. Therefore, the QC must be performed as the parts (subassemblies) are fed into the MMM and with a frequency of 0.11 Hz or higher.

Table 1: Overview of the characteristics and KPIs for PEMFC stacks, the Fit-4-AMandA's targets and the baseline [1]

Characteristics and Key performance indicators (KPIs)	Fit-4-AMandA targets	Baseline
Production time for one stack (throughput time)	<0.5 h	40 h
Automated production process steps	90 % automation grade per stack	10 % automation grade per stack
Testing time (automated and manually)	1 h	24 h
Costs per stack	>50 %	100 %
Reduction of scrap (e.g., broken BPPs per stack during production)	0	10 per stack
Non accepted tests: Rework and unbundling of stack	0	Every 10th stack needs to be reworked
Tightness and leakage of the stack	0	Every 10th stack needs to be reworked

Within the scope of the Fit-4-AMandA project for several reasons as explained in more detail in the confidential report D5.1, it was not possible to procure and implement the full setup of QA instrumentation as primarily intended. Nevertheless, TUC as the leading partner of this essential part has successfully arranged demonstrations by the producers of the relevant QC hardware and software to gauge the feasibility of the most promising candidate methods. This assessment will be very helpful in the next expansion levels of the MMM after the projects end.

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[2] Porstmann, S., et al.: Overcoming the challenges for a mass manufacturing machine for the assembly of PEMFC stacks. Machines 7: 1–20, 2019. https://doi.org/10.3390/machines7040066.

3 Down-selection of the method candidates from D5.1 and the lab-scale tests

In the confidential report D5.1, the method selection was optimised in order to minimise the testing time allowing the stacking process to reach its maximum throughput without creating a bottleneck. Among considered QC candidates were for example machine-vision systems and infrared (IR) thermography. Potentially hazardous QC methods such as X-ray radiography were excluded. The methods together with achievable production speeds are listed in Table 2. More details can be found in the confidential report D5.1. The MMM is modular and therefore it can be retrofitted with additional modules (e.g., for QC or additional stacking modules; see greyed modules in Figure 1) using only minor changes in its configuration.

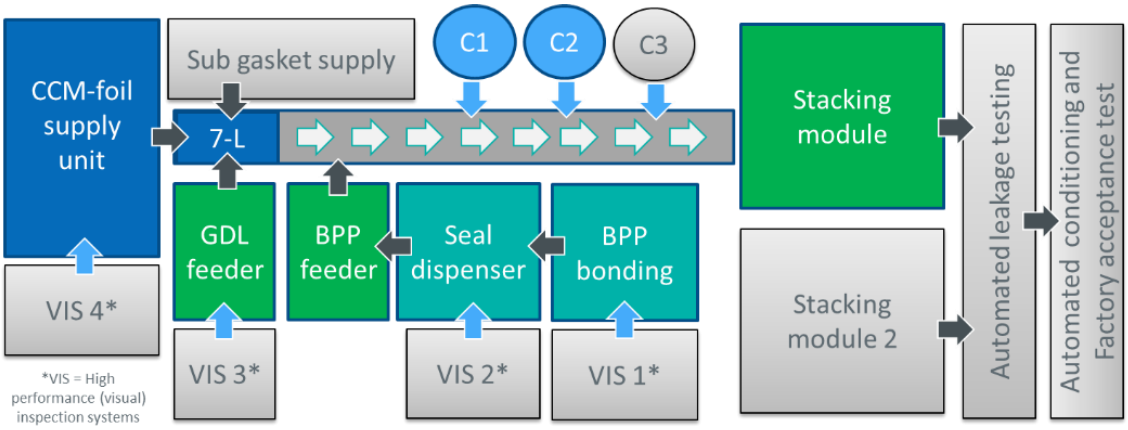

Figure 1: Modular character of the MMM with greyed modules signifying expansions.

Table 2: Overview of in-line qualitative methods for testing fuel cell components as presented in the confidential report D5.1.

Component/ sub-assembly	Detectable defects	Minimum detectable defect	Method	Supported production speed / estimated time per plate (for half plates/BPPs)
CCM/GDE	Catalyst-loading defects	0.01 mg-Pt/cm²	XRF [3]	N.A.
GDE[4]	Catalyst-loading defects	0.04 cm²	IR/RIF	15.2 cm/s
CCM	Catalyst-loading defects, lumps, cuts, scratches, die line, start/stop defects	0.04 cm²	IR/DC (in-plane configuration)	15.2 cm/s
MEA	GDL fibres protruding into the membrane, pinholes, cuts, and scratches	N.A.	IR/DC (through-plane configuration)	15.2 cm/s
Half plate/BPP	Hair-cracks, land breakage, and possibly other moulding defects	10 µm	Area-scan camera	1-2 s [5]
		10 µm	Line-scan camera	1-2 s [5]
		10 µm	Focus variation	6 min [6]
Sealing bead	Irregularities in height and width	100 µm	Laser triangulation	1 s [7] or >250 mm/s [8]

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[3] At higher linear speeds method allows only a random sampling.

[4] A study needs to be performed to ascertain, whether the IR/RIF method can be applied on CCM, too.

[5] 100-% integrity test of the whole plate (164 mm x 369 mm). For details, see Section 4.2 in D5.1.

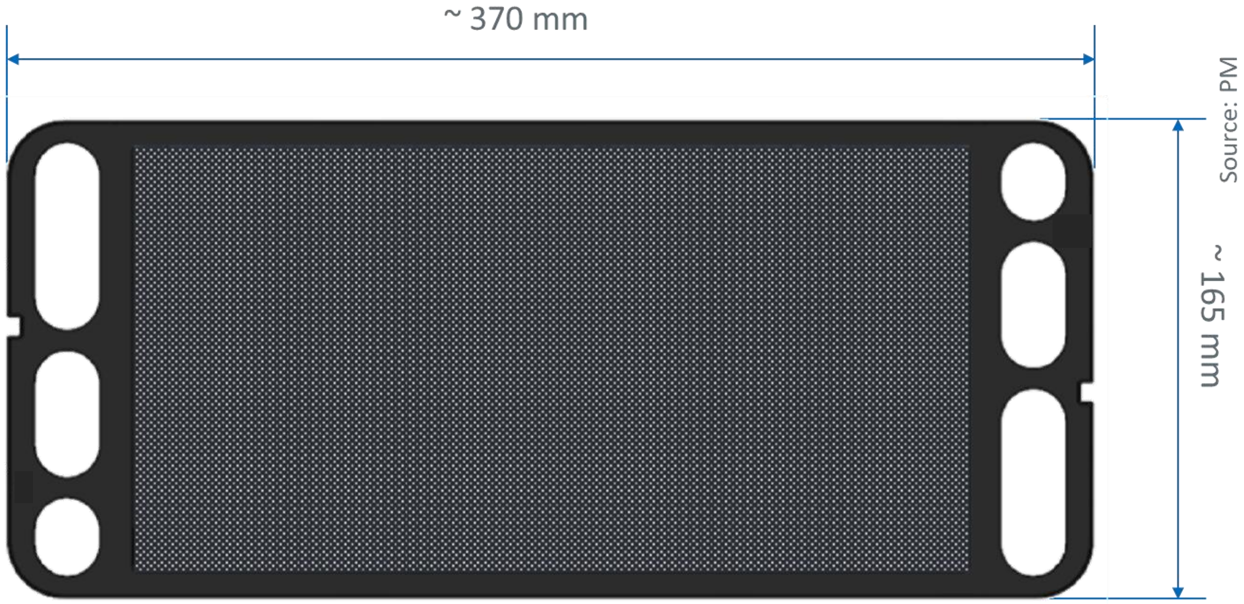
[6] Mentioned here just for comparison.

[7] Post-process inspection of sealings on the whole plate (164 mm x 369 mm). For details, see Section 4.2 in D5.1.

[8] In-process inspection. Depends on a frequency of the chosen profiler. For details, see Section 4.2 in D5.1.

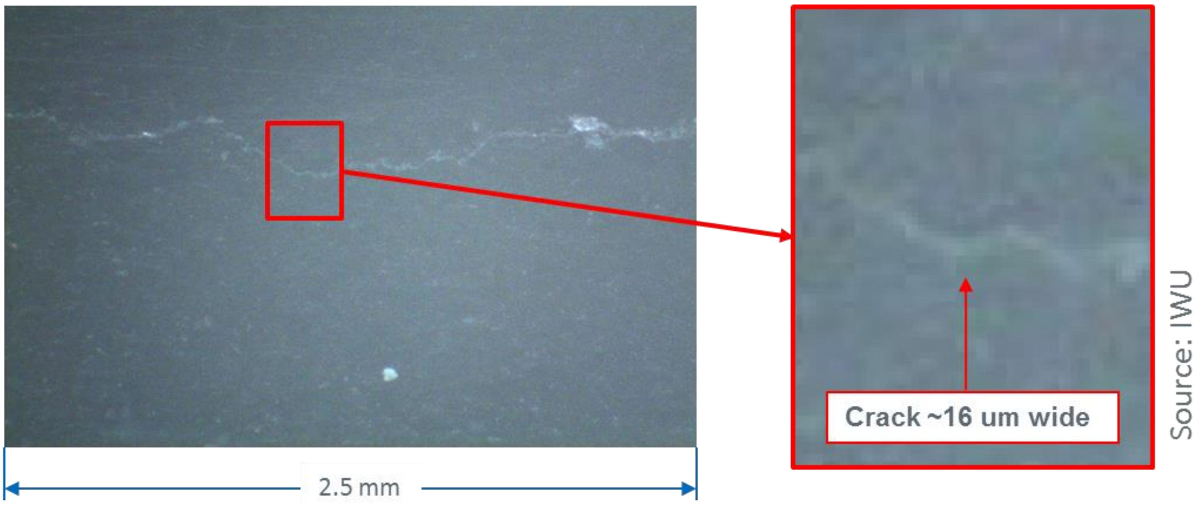
3.1 Half/bipolar plate testing

As discussed in the confidential report D5.1, hair-cracks in graphite-polymer composite BPPs are responsible for the internal and external leakage in the resulting PEMFC stacks. Any leakage test performed on the BPP does not meet the time constrains of 9 seconds [9]. An investigation using so-called machine-vision systems was selected as the most suitable candidate (see the confidential report D5.1). The extremely high aspect ratio of such hair-cracks (long but narrow) together with a large surface area of the PM400 plate (see Figure 2) necessitates a very high spatial resolution of the instruments. A PM200 plate with its smaller area requires lower specifications of the QC instrumentation, thereby all considerations were made for the PM400 plate as the worst-case scenario. In D5.1, a result of an offline detection of the hair crack (see Figure 3) was presented.



Source: PM

Figure 2: A PM400 plate with dimensions (a depiction of flow field is omitted for confidentiality reason).



Source: IWU

Figure 3: An image showing a hair crack captured by the IDS camera with micro-optics.

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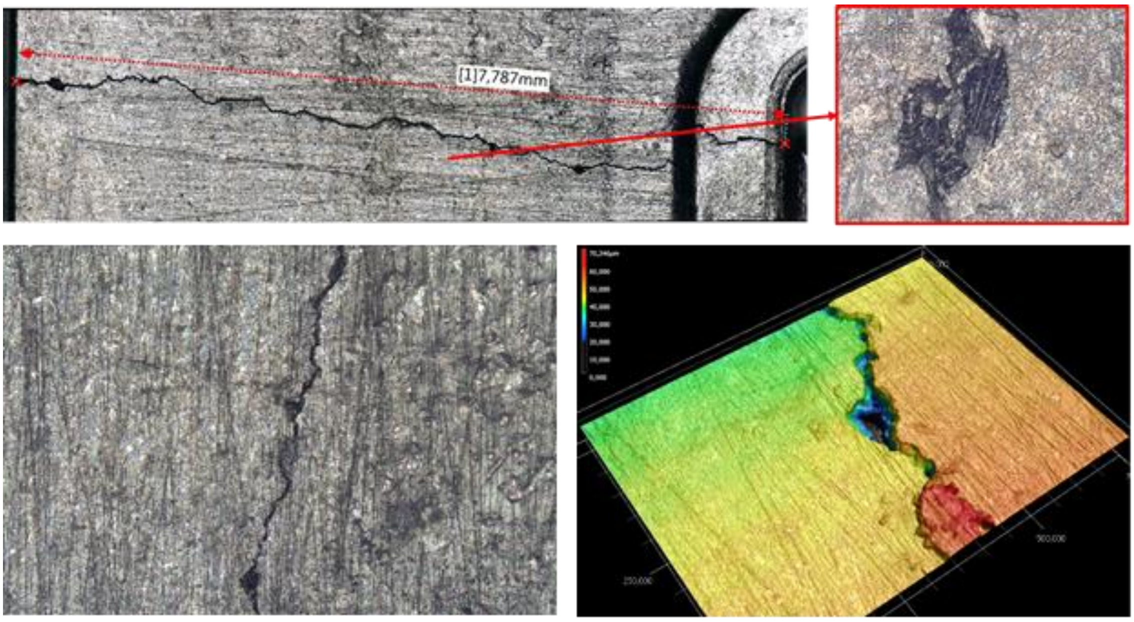
[9] Private communications with the company Marposs in 2019 and 2020.

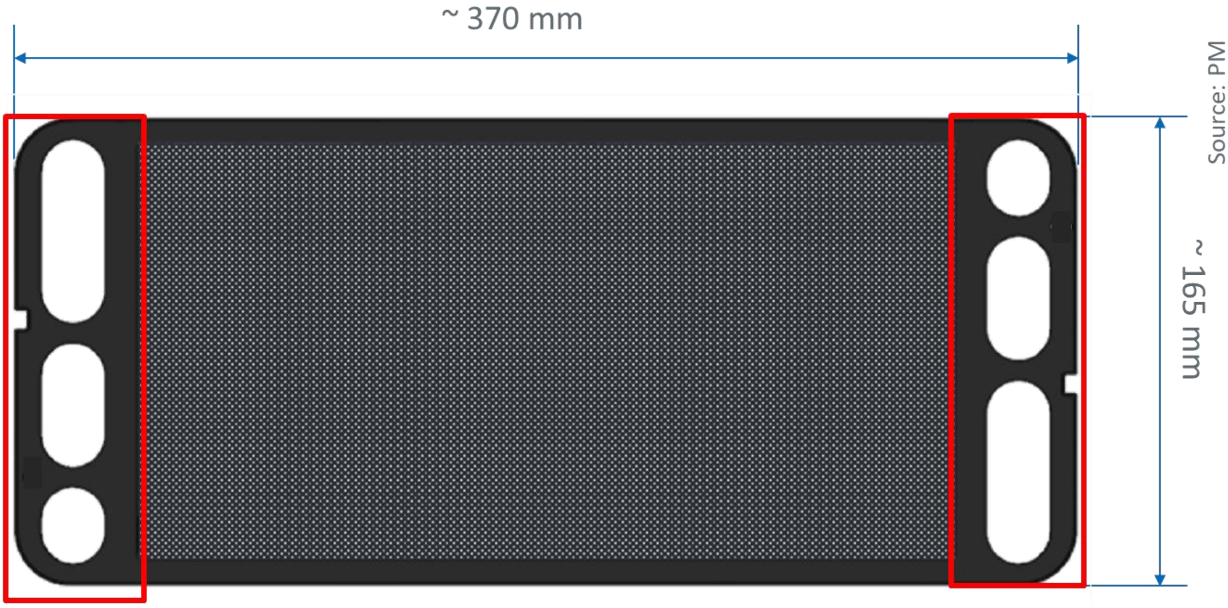
Additional tests with KEYENCE’s digital and laser-scanning microscopes (see exemplarily Figure 4), were able to provide on-line 3D image of half plate surface with a hair crack. Although the inline detection with these would not be feasible, because of insufficient speed of measurement, data from the measurements helped to establish the requirements for the future inline inspection.



Source: KEYENCE

Figure 4: Results of the tests performed on the half plate from PM using the KEYENCE’s VK-X 1000 laser-scanning microscope.

The update of the PM400 and PM200 footprint (see Figure 6), which was done to enable an easier automated handling by the MMM, eliminated the protrusion seen on the left picture in Figure 6. This should reduce the risk of breakage during the handling in the MMM. A further study would be required however to ascertain, whether the probability of the hair-crack formations was reduced, too.



Source: PM

Figure 5: PM400 plate with marked surroundings of manifolds most susceptible to a hair crack formation.

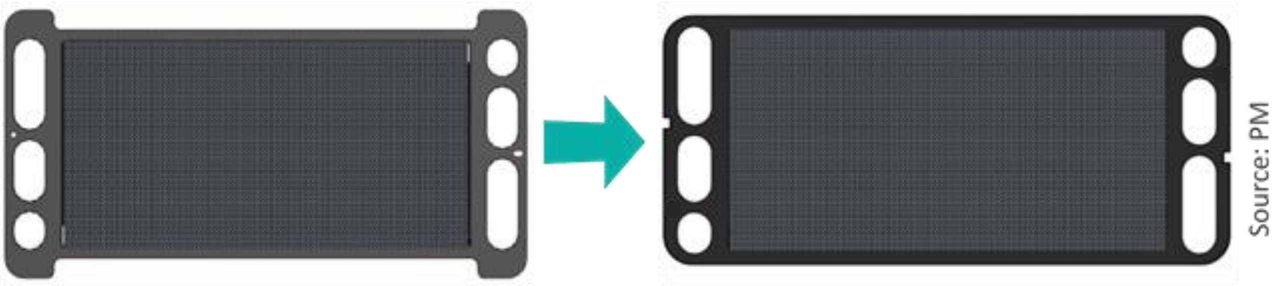


Figure 6: Updated footprint of the PM400 plate.

During unsuccessful inline test with the KEYENCE's 3D profiler LJ-V (see Figure 7), only the widest part of the hair crack (barely visible in the right picture, approximately 50 µm in width) was detected with the number of pixels too low for a reliable defect detection. In further cooperation with KEYENCE, more successful tests were performed using a KEYENCE's customizable vision system with a line-scan camera support XG-X consisting of a line-scan camera LumiTrax combined with a dedicated lighting module producing high-speed striped LED lighting, which enhances contrast of the hair cracks making them visible for the inline inspection (for more details, see the confidential report D5.3).

With XG-X, hair cracks with a width of approximately 30 µm can be reliably and automatically detected (see Figure 8) using KEYENCE's image capture and processing algorithms. With one camera, a cycle time of approximately 4.5 minutes for the PM400 plate (resolution 3.3 µm) can be achieved. To reduce this time, either the resolution can be reduced, which is not recommended, multiple cameras used, which increases overall costs but provides shorter cycle time, or the recording conditions optimized. Because the parts of a plate with the manifolds are most prone to a hair-crack formation, the scanned area could be reduced (see Figure 5).

Further optimization of the recording conditions and configurations through a large-scale study (testing of large number of PM400 plate to build up a statistics) is required to bring the price down.

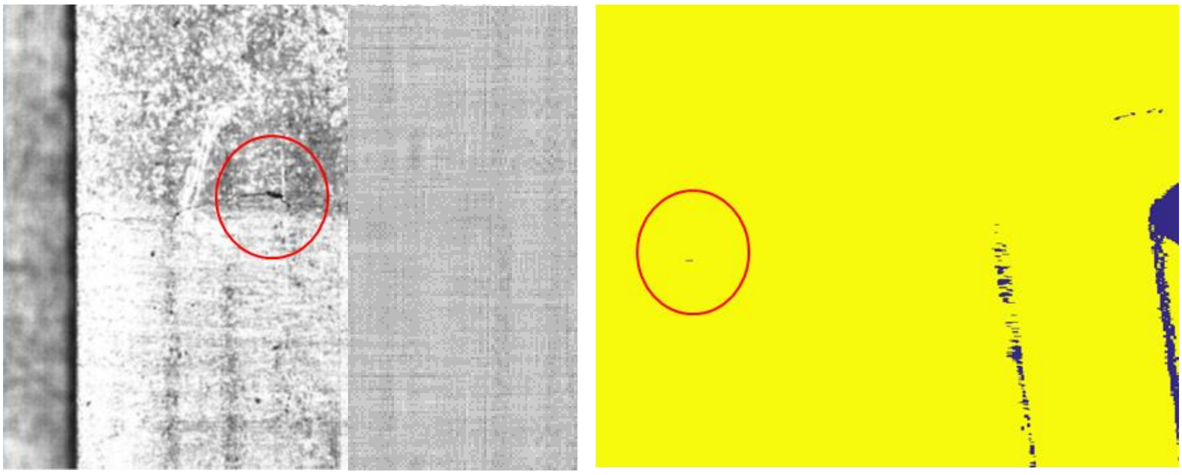


Figure 7: On the left, an optical image of the hair crack obtained with the KEYENCE's line-scan camera; on the right, an unsuccessful test with a laser profiler LJ-V from KEYENCE. The widest part of the hair crack is marked by a red circle.

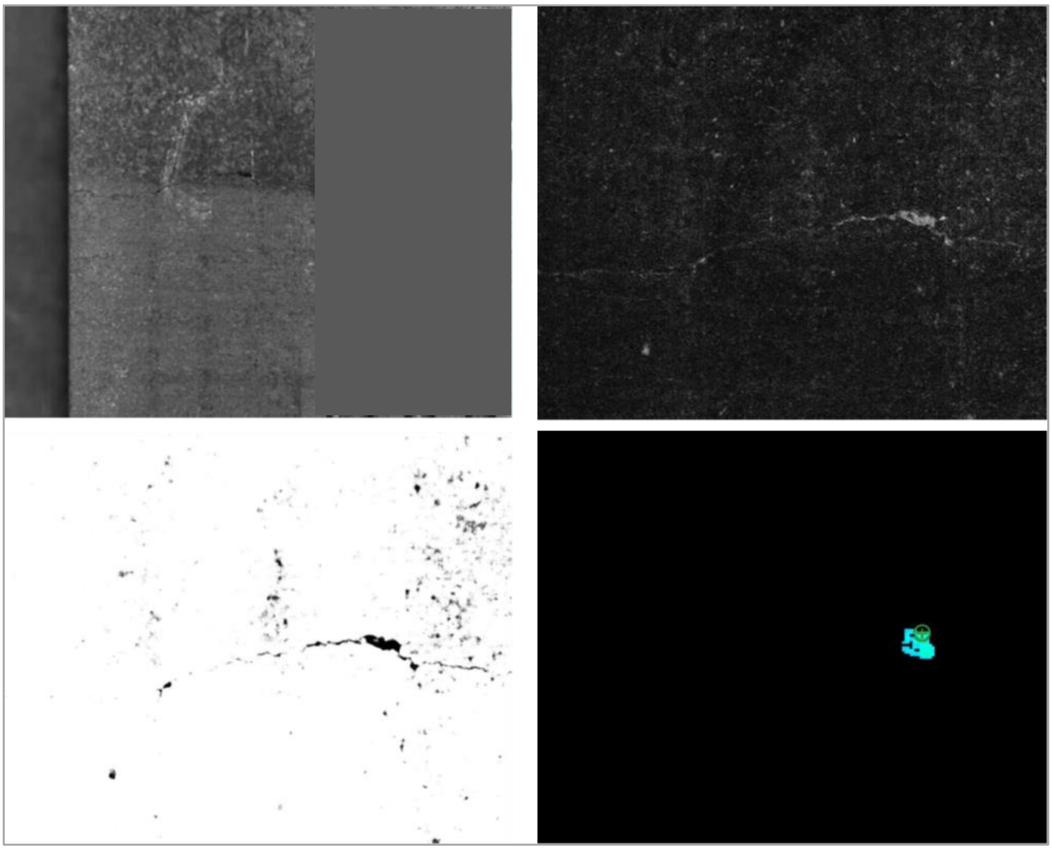


Figure 8: A successful detection at KEYENCE: Upper left, a normal picture from a line-scan camera; upper right, a magnified hair crack; bottom left, magnified hair crack after image processing using filters; bottom right, a hair crack (wider part) successfully detected.

If the half-plate bonding to BPP takes place inside the MMM, i.e., the half plates instead of BPPs are fed into the MMM, a QC of the half plates would be needed. In this case however, a double frequency of QC (double number of cameras) would be required, because each BPP consists of two half plates. An advantage of such solution would be that the cooling sides of each half plate could also be investigated and a possible hair crack which does not run through the entire thickness of the plate and it is therefore not visible for the QC on the gas side of the plate. Given the thickness of the PM400 plate, a formation of such crack is however improbable.

3.2 MEA/CCM quality control

In the confidential report D5.1, a series of QC methods was proposed as viable options for the QC of the CCM/MEA. In particular, the IR/DC active thermography (see Figure 9 and Figure 10) shown much promise. [10] Because the instrumentation for such method (or similar) vastly exceeds the budget available in the Fit-4-AMandA project, a lab-scale tests were not performed. However, extensive discussions on this topic were led with members of the research team from National Renewable Energy Laboratory (NREL), which developed said methodology and successfully tested it on an industry-grade production line [10], regarding applicability and the further development. Moreover, the method can be applied by anyone, assuming funds are available (approximately 190 € [11]), because it stems from a public funded research and it is not tied to any patent.

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[10] Ulsh, M.: Fuel Cell MEA Manufacturing R&D. DOE Fuel Cell Technologies Program Annual Merit Review 2013-2017.

[11] James, B. D., et al.: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2017 Update.

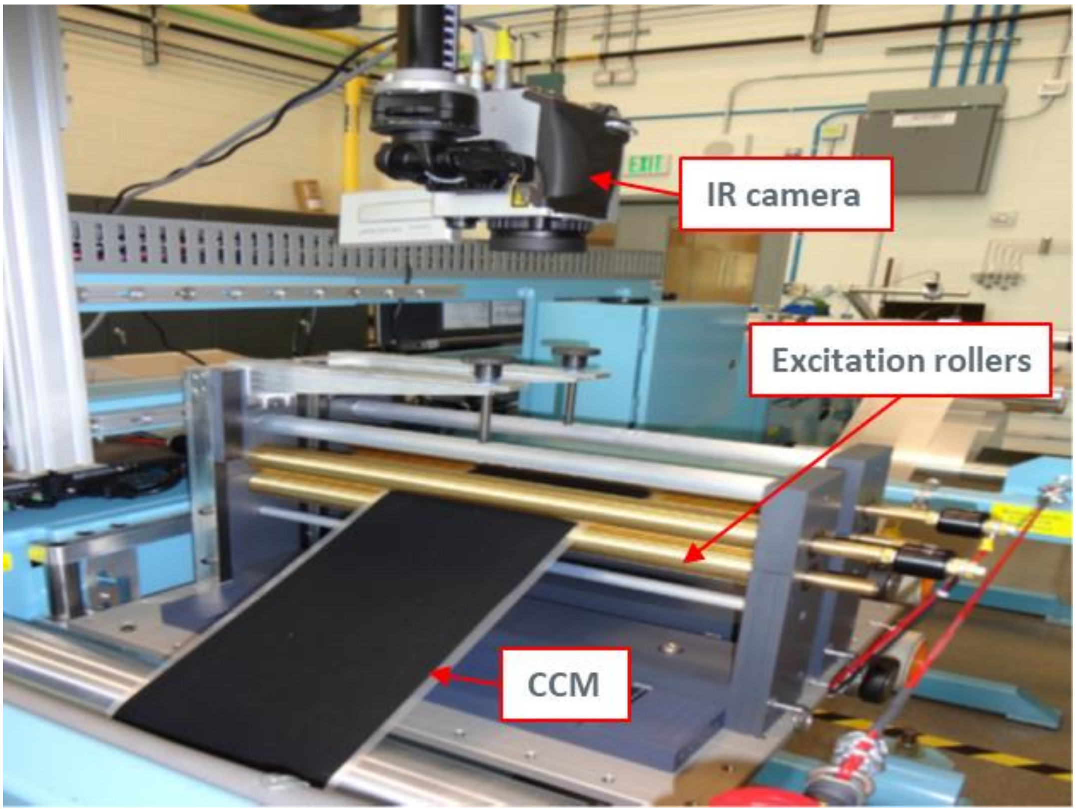


Figure 9: The setup used by NREL for an in-line IR/DC technique.

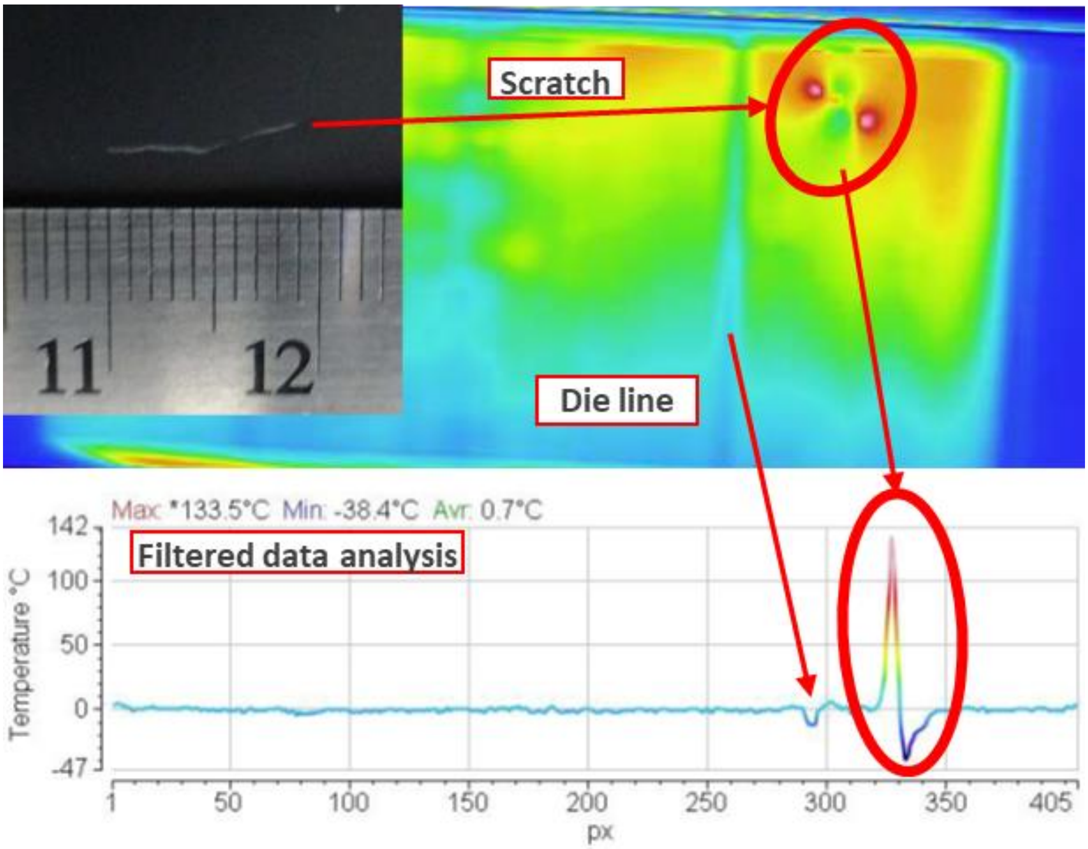


Figure 10: An example of defects (scratch and the "die line") detected using the in-line IR/DC technique.

3.3 Sealing quality control

The strategy of the investigation of the sealing bead by the 3D profiler was already extensively described in the confidential report D5.1. The scanning procedure is illustrated in Figure 11.

When using a PM's robot dispenser, the sensor can be mounted directly on the dispensing nozzle. Because only a small section of the sealing bead is scanned at a time, an employment of a 3D profiler model with a shorter *x*-range and thus higher frequency and better resolution is viable. The following formula gives the relation between dispensing speed v_{disp}, frequency *F* and resolution Δy.

$$v_{\mathrm{disp}} = \frac{F}{N} \cdot \Delta y \, .$$

The resolution Δy determines the smallest detectable gap size in the sealing bead. *N* is the number of samples required to detect reliably the gap in sealing. A can be seen from the formula above, the dispensing speed scales linearly with the frequency of the used sensor. For more detail, see the confidential report D5.1.

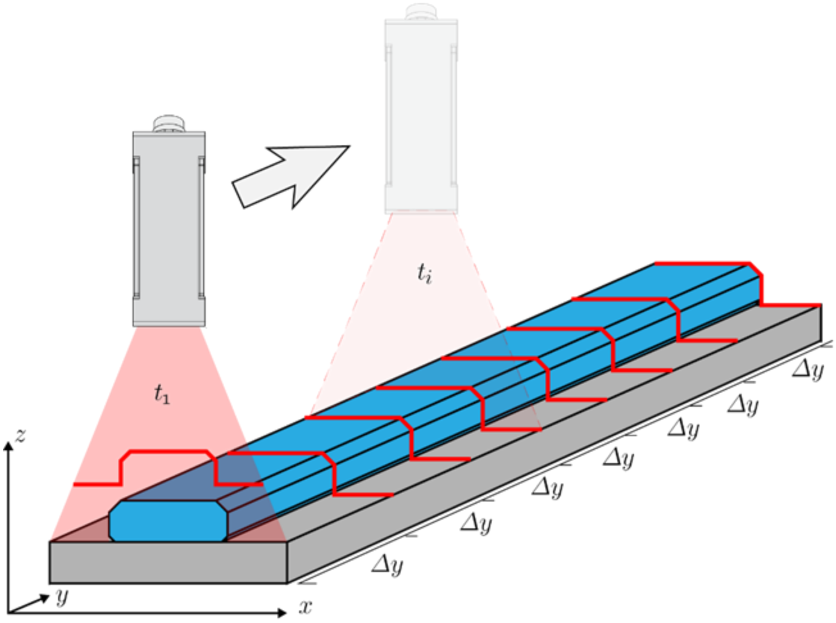
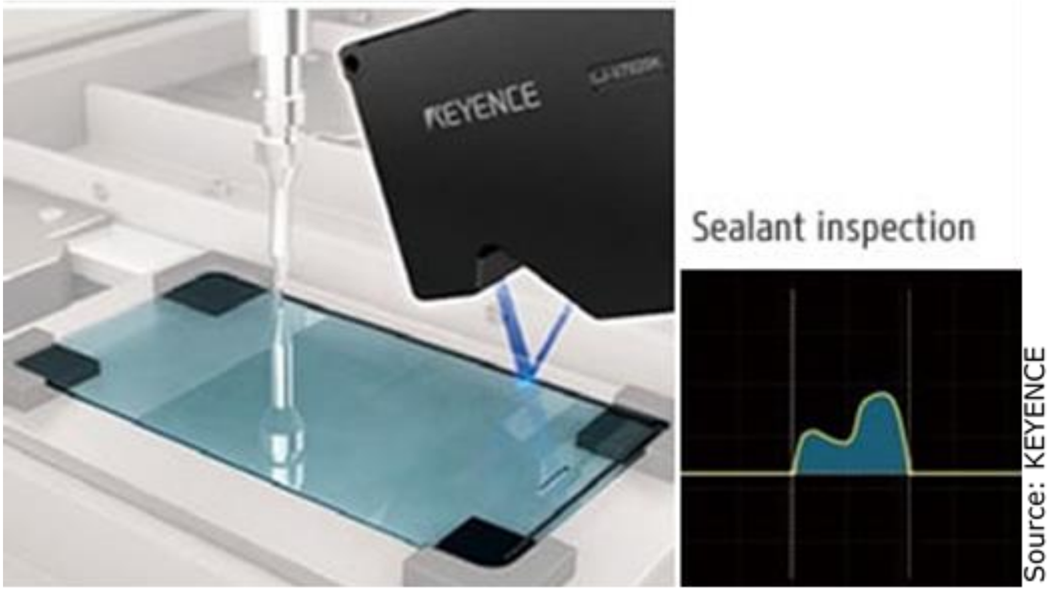


Figure 11: An illustration of the scanning process and collecting profiles (red) of the sealing bead (blue).

The results of the tests with KEYENCE’s 3D profiler (see Figure 12) shown that the transparent sealing bead is not suitable for this form of detection (see Figure 13). Based on these findings, a colour additive was recommended to PM. Assuming a non-transparent sealing bead, the sensor such as KEYENCE’s sensors from the LJ-V7000 series is sufficient for the task. Such a configuration would allow dispensing speeds of up to $v_{\mathrm{disp}} = 250$ mm/s (assuming $\Delta y = 0.1$ mm, $N = 4$, $F = 10000$ Hz). This assumes the usage of own computer to evaluate the signal using software from KEYENCE.



Source: KEYENCE

Figure 12: KEYENCE’s sensor from the series LJ-V.

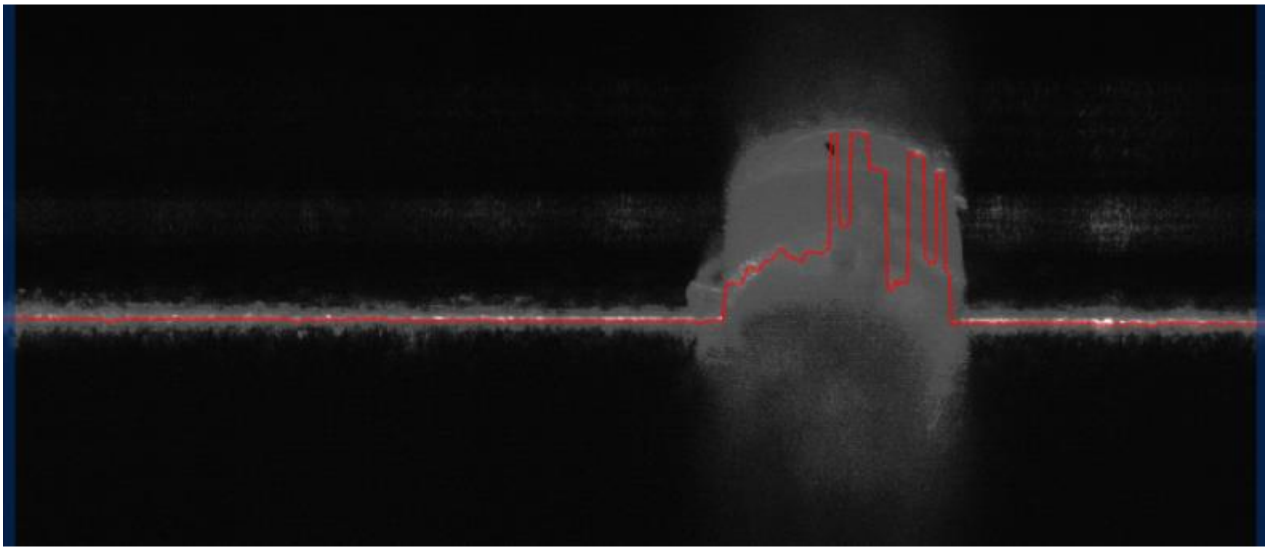


Figure 13: A result of the unsuccessful feasibility test – scanning of the transparent sealing bead with the blue laser LJ-V profiler from KEYENCE.

4 Large-scale tests

The large-scale tests of the QC methods for BPPs directly at before the feed into the MMM as well as the tests of the QC methods for the sealing performed directly on the PM's dispensing robot during dispensing (in-process) were postponed due to the global pandemic of COVID-19. When the situation improves, these tests and the implementation of the QC methods will continue, although outside of the scope of Fit-4-AMandA.

5 Conclusions and recommendations

This report is a public version of the confidential report D5.4. A selected information is presented. For more details, see the confidential report D5.4 and the public report D5.5.

Currently, only the vision system with the two cameras for positioning (for more details, see the confidential report D4.7) was implemented into the MMM. The implementation of the remaining QC waits until the COVID-19 global pandemic will subside to a degree, when the face-to-face collaboration between partners and companies providing testing hardware is possible again.

Nonetheless, the consortium is in the meantime still active as the topic of inline QC of PEMFC components is gaining much attention in the fuel cell community. Upcoming international online workshops and webinars (such as ones organised by VDMA), national QC workshops organised by TUC, international online fuel-cell conferences (such as Hydrogen Days 2021 coming in March) are just examples of opportunities to disseminate the project, exploit its results, and continue in collaboration.

Although not all possibilities of QA have been implemented directly in the first phase of MMM, the basic preparations have been made in this work package in order to implement them in the upcoming expansion stages. This is also planned by the project partners after the end of the project.

6 Risk Register

Table 3: Risk register.

Risk No.	What is the risk	Probability of risk occurrence	Effect of risk	Solutions to overcome the risk
1	Methods will not be fast enough at given production rate or will not provide needed resolution	Low	Medium	1. Re-evaluate/update the search. 2. Use the combination of several slower methods to infer the relevant data at high throughputs.
2	The actual stacking machine will be more expensive than expected, preventing the procurement of QA instrumentation	High [12]	Medium	1. Ascertain the feasibility of the most promising candidate methods during (free) demonstrations by the producers of the relevant hardware. 2. Improvise some of the methods using similar (available) hardware to prove the concept (not relevant for the actual implementation). 3. Implement the cheapest solution and possibly retrofit the stacking machine with the QA instruments after the conclusion of the project independently (not planned within TUC's budget)
3	Methods will be too expensive to implement in the scope of the project	High [12]	Medium	Methods will be implemented outside from the scope of the project.

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[12] It occurred already.

7 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner	Partner Full Name
1	UNR	Uniresearch BV
2	PM	Proton Motor Fuel Cell GmbH
3	IRD	IRD Fuel Cells A/S
4	Aumann	Aumann Limbach-Oberfrohna GmbH
5	Fraunhofer	Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung e.V.
6	TUC	Technische Universitaet Chemnitz
7	UPS	UPS Europe SA

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This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 735606. This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY.
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