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

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1 Publishable executive Summary

In the scope of the project Fit-4-AMandA[1], a mass-manufacturing machine (MMM) for polymer-electrolyte membrane fuel-cell (PEMFC) stacks was developed and built. The MMM can increase the production volumes of the PEMFC stacks and in so reduce their price through economy of scale. [2]

One of the essential prerequisites for being able to manufacture any product in high quantities and high quality is good quality assurance in the process, adapted to the respective cycle times and quantities. Of course, this also applies to MMM. Here, a wide variety of measurement tasks occur to ensure the identification of defects during the production of the fuel cell stack or the stacking process.

In this report, a selection from quality-assurance protocols using inline quality control (QC) for with a non-destructive testing (NDT) suitable for PEMFC stack's repeating parts such as bipolar plates (BPPs), membrane-electrode-assemblies (MEAs) and catalyst coated membranes (CCMs) is proposed. Moreover, the protocol for the QC of the sealing is included, too.

Therefore, concrete test procedures and protocols have been identified, investigated and assessed with regard to the suitability for their specific task. Finally, the methodologies, test equipment, evaluated test protocols and their potentials are described in detail.

Together with the confidential report D5.4, the report D5.5 gives a comprehensive overview of the state-of-the-art of the quality-assurance methods used in PEMFC stack sector.

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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] 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.

2 Introduction

The development of NDT-QC tools for the PEMFC-stack production line is vital to increase yield and reliability of the mass-produced PEMFC stacks. Low production throughputs and high number of faulty produced PEMFC stacks (every tenth stack is faulty and needs to be reworked[3]) are among the main technical barriers in the fuel cell stack manufacturing. Furthermore, fast quality-testing techniques are lacking. [4] The goal of Fit-4-AMandA project is to elevate these constraints, and fast NDT-QC methods are necessary in order to do so.

There are three levels at which NDT-QC can be applied:

- A QC performed at a component level, i.e., fuel cell components such as half plates, GDLs, membranes, and gaskets are tested for relevant faults;
- A QC performed at a sub-assembly level, i.e., QC of MEAs/CCM, BPPs, or even single cells;
- A QC performed at a stack level, i.e., the stack is tested as it is assembled and after the assembly is finished.

The last option was the proposed idea in the Fit-4-AMandA project. 5-cell blocks were to be tested during the stack assembly (see Figure 1). Mechanical (pressure decay test) and electrochemical methods (OCV decay test, fuel crossover measurements, CVM, etc.) were to be used to detect a possible leakage. This concept was abandoned, because the required compression of the cell blocks would irreparably damage the MEA (e.g., by breakage of PFTE coating in the GDL). For more details, see the confidential report D5.1.

Alternatively, that stack could be built from repeated single cells (see Figure 2), which would need to be made tight in order to perform the tightness test. Similar concept was employed in the production line co-developed by ZBT in 2012. [5]

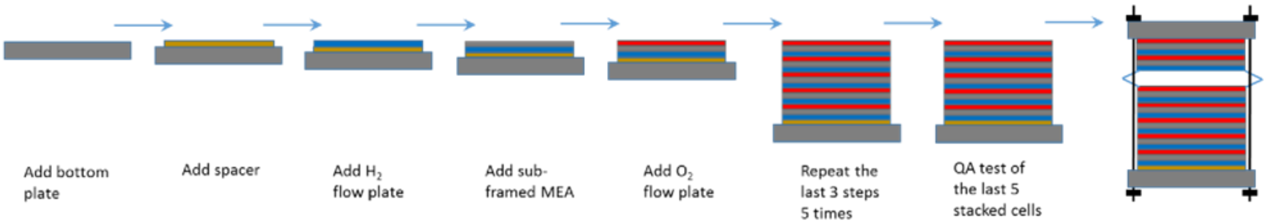

Figure 1: Stack assembly process proposed in the Grant agreement of Fit-4-AMandA project.

The first two options are inspired by a prevalent practice in the automotive industry, where the assumption was made that if the parts are healthy and the production line can keep tolerances during the assembly, then the resulting product should perform according to the specifications. Such assumption requires two important prerequisites:

1. The process must be mature enough to guarantee a low scrap ration in the end product (assuming healthy parts are entering the production process).
2. The faults of the components or subassemblies, which cause failure modes in the end products must be known.

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[3] Biak, M.: Non-destructive quality control and testing tools, Newsletter #2, April 2018, Fit-4-AMandA – 735606. http://fit-4-amanda.eu/download/project_flyer_newsletters/Fit-4-AMandA-Article-Non-destructive-quality-control-and-testing-tools-TUC.pdf [Accessed Jan. 14, 2021].

[4] U.S. Department of Energy, "Fuel Cell Technologies Office Multi-year Research, Development, and Demonstration Plan", 2015. http://energy.gov/sites/prod/files/2015/06/f22/fcto_myrdd_manufacturing.pdf [Accessed Jan. 14, 2021].

[5] Beckhaus, P.: Production and automation for fuel cells and components – R&D supporting industrial processes, f-cell, Stuttgart, 08.10.2012. https://www.zbt.de/fileadmin/user_upload/01-aktuell/05-publikationen/05-vortraege/2012/F-Cell2012-beckhaus-2012v4.pdf [Accessed Jan. 14, 2021].

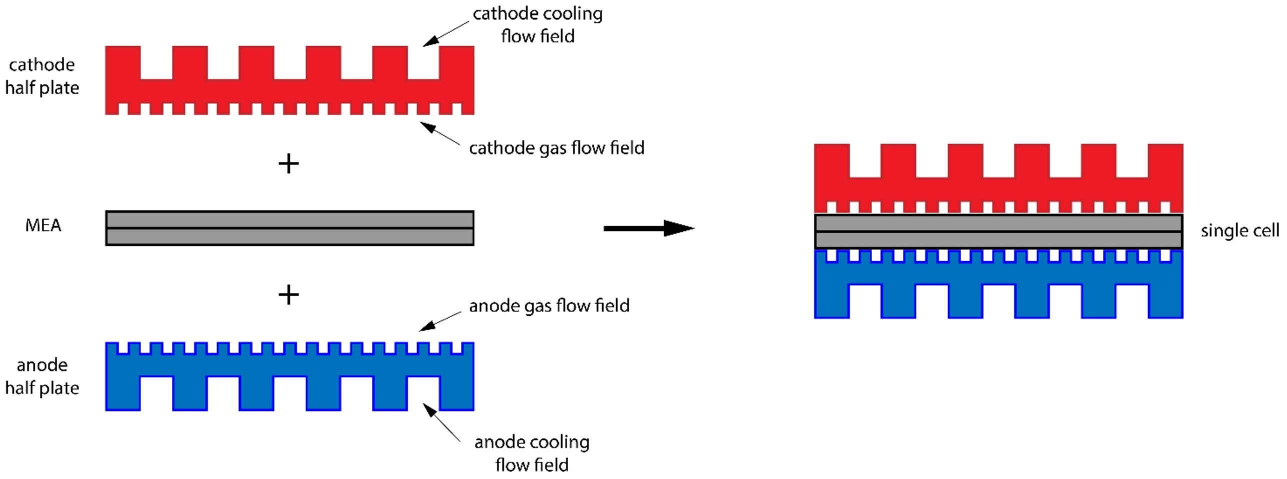

Figure 2: Single cell sub-assembly created from anode and cathode half plate and the MEA.

The process maturity comes usually as the time progresses and the experience with the production process is gathered. On the other hand, tracking the causes for the product's failure modes upstream in the production process to faults of the entering components/subassemblies is a major undertaking, which in the fuel-cell industry is not nearly as far as needed. However, since the project Fit-4-AMandA started, its consortium observed that the QC of fuel cell component, in particular the inline QC, starts gaining much needed attention. Partners from the Fit-4-AMandA consortium participated at several workshops (national and international) focused on the topic of QC in fuel cell manufacturing [6;7;8;9], where the representatives from fuel-cell industry, suppliers of testing hardware and researchers from research institutions and universities shared information on their activities and discussed the challenges arising in the FC production and how they can be overcome.

Additionally, TUC organised inter-project meetings with partners from the project MAMA-MEA [10], namely JMFC and INEA, focused on the options of implementing QC in the production line for MEA. Naturally, during these meetings, nothing was shared that would breach the projects confidentiality as specified in Consortium Agreement of each project (Fit-4-AMandA and MAMA-MEA).

These efforts will continue even after the conclusion of the Fit-4-AMandA project, because the MMM developed in the project will require additional upgrades from PM to reach the full performance potential and hence assure its competitiveness. Furthermore, Aumann will include an option of addition QC systems to the PEMFC-stack production line manufactured in future. IRD is already considering an inclusion of QC in the BPP.

TUC will be able to utilise gained know-how in other projects (both, currently running and acquired in the future). Furthermore, some of the project partners communicated their strong interest of further collaborations with the TUC in this field. Especially when improving the MMM to the next extension stage the gained knowledge will be required.

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[6] Canada-Germany Workshop »Fuel Cell Component Quality, International Workshop, Freiburg, Germany, 18.09.2018.

[7] VDMA AG BZ Workshop - Quality assurance of PEMFC components (International Workshop), Duisburg, Germany, 02.-05.06.2019. https://bz.vdma.org/en/viewer/-/v2article/render/35419357 [Accessed Jan. 14, 2021].

[8] VDMA AG BZ Workshop - Automated manufacture of PEMFC Stacks (International Workshop), Duisburg, Germany, 28.-29.01.2020. https://www.vdma.org/en/kalender/-/event/view/53086 [Accessed Jan. 14, 2021].

[9] VDMA Working Group Fuel Cells - International Web Seminar "Factory Acceptance Testing & Break-in of Fuel Cell Stacks", online, 01.-02.10.2020. https://my.vdma.org/kalender/-/event/view/58488 [Accessed Jan. 14, 2021].

[10] Mass Manufacture of MEAs Using High Speed Deposition Processes – MAMA-MEA (EU project, duration 01 Jan 2018 – 30 Jun 2021, 42 months). Funding Programme H2020-JTI-FCH-2017-1, Grant Agreement #779591.

3 Specification of the requirements

The critical entries into the stacking process are BPPs and MEAs. After consulting the available literature as well as gathering the experience of the industrial partners (Aumann, PM and IRD), the following tests were focused on (see D5.1):

- integrity and tightness tests of every BPP,
- tests of the MEA for defects typically occurring after hot-pressing,
- in-process and post-process quality control (QC) of sealings in the stack.

For each category, a set of requirements was established after thorough consideration based on the investigation of the samples provided by PM and IRD (for details, see the confidential report D5.4 or for selected information its public version D5.6), PM's experience as well as expertise gathered from other subjects in the fuel cell industry during aforementioned workshops and other dissemination activities. The inline QC methods selected in D5.1 were then down-selected based on whether they are able to fulfil these requirements (see Section 4).

3.1 Half/bipolar plates

The following requirement were defined based on the investigation of samples of half plates and BPPs provided by PM and IRD and on the PM's experience:

1. No hair cracks as small as 10 µm in width;
2. No deviation in the mean thickness of the plate larger than ±50 µm (based on the thickness of the PM400 plates);
3. No deviation in the mean plane parallelism of the plate larger than ±25 µm (based on the thickness of the PM400 plates).

3.2 MEA/CCM quality control

The assembly of MEA (more precisely a CCM) was not planned as an integral part of the MMM; therefore, the QC of MEAs was to be performed on the MEA supplier side. The possibilities of implementing QC on the future production of IRD were discussed.

The following requirements are based on defects that can be successfully detected inline using methods listed in the confidential report D5.1 and in Section 4.2:

1. No added material, so-called "lumps", as small as 1 mm in diameter;
2. No surface scratches of area as small as 4 mm²;
3. No surface cuts of length as small as 5 mm;
4. No bare spots (spots on the catalyst layer with considerably lower catalyst loading, i.e., <50 % deviation) with a surface area as small as 4 mm²;
5. No so-called die line in a coated electrode layer;
6. No so-called start/stop defects (result of an in-process adjustment during the coating process).

3.3 Sealing quality control

After the discussion with PM and considering the possibilities of PM's dispensing robot, it was decided that a detection of a deviation as small as of 0.1 mm in width or height of the sealing bead would suffice. A sealing QC would be performed in two ways:

1. A 100-% detection of deviations in either width or height would be performed in-process, i.e., during dispensing of the sealant.
2. A sample of the plates with a size of 1 %, i.e., every one-hundred plate, would be tested post-process after the hardening of the sealing to detect possible deviation in width or height.

4 Description of the measurements and proposed quality-assurance protocols

No precise quality-assurance protocols could be established, because no methods were implemented into the MMM or tested directly on MMM due to the budgetary reasons (see the confidential report D5.1) and due to the limitations caused by the global pandemic of COVID-19 (see the confidential report D5.4 and its public version D5.6). Only proposed protocols are given.

More details regarding the methodology reasoning can be found in the confidential reports D5.1 and D5.4.

4.1 Half/bipolar plate testing

In the following, the focus is on PM400 plate (a large plate). The PM200 plate would require less extensive instrumentation.

In order to detect the hair cracks on the PM400 plate (bipolar plate or half plate) with the required frequency of 0.11 Hz, a customizable vision system von KEYENCE (see Figure 3) consisting of 16 line-scan cameras, 8 dedicated lighting modules producing high-speed striped LED lighting, which enhances contrast of the hair cracks making them visible for the inline inspection, and 8 controllers can be used. Using KEYENCE's image capture and processing algorithms, hair cracks with a width of approximately 30 µm can be reliably and automatically detected (see Figure 4) on the high risk regions of PM400 plate (approximately 50 mm x 165 mm per region; see Figure 5), which are, as explained in the confidential report D5.4, most susceptible to a hair-crack formation.

Figure 3: KEYENCE's customizable vision system with line-scan camera support XG-X series: line-scan camera LumiTrax (left) with the high-speed striped LED lighting module (right) and with marked scan direction.

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.

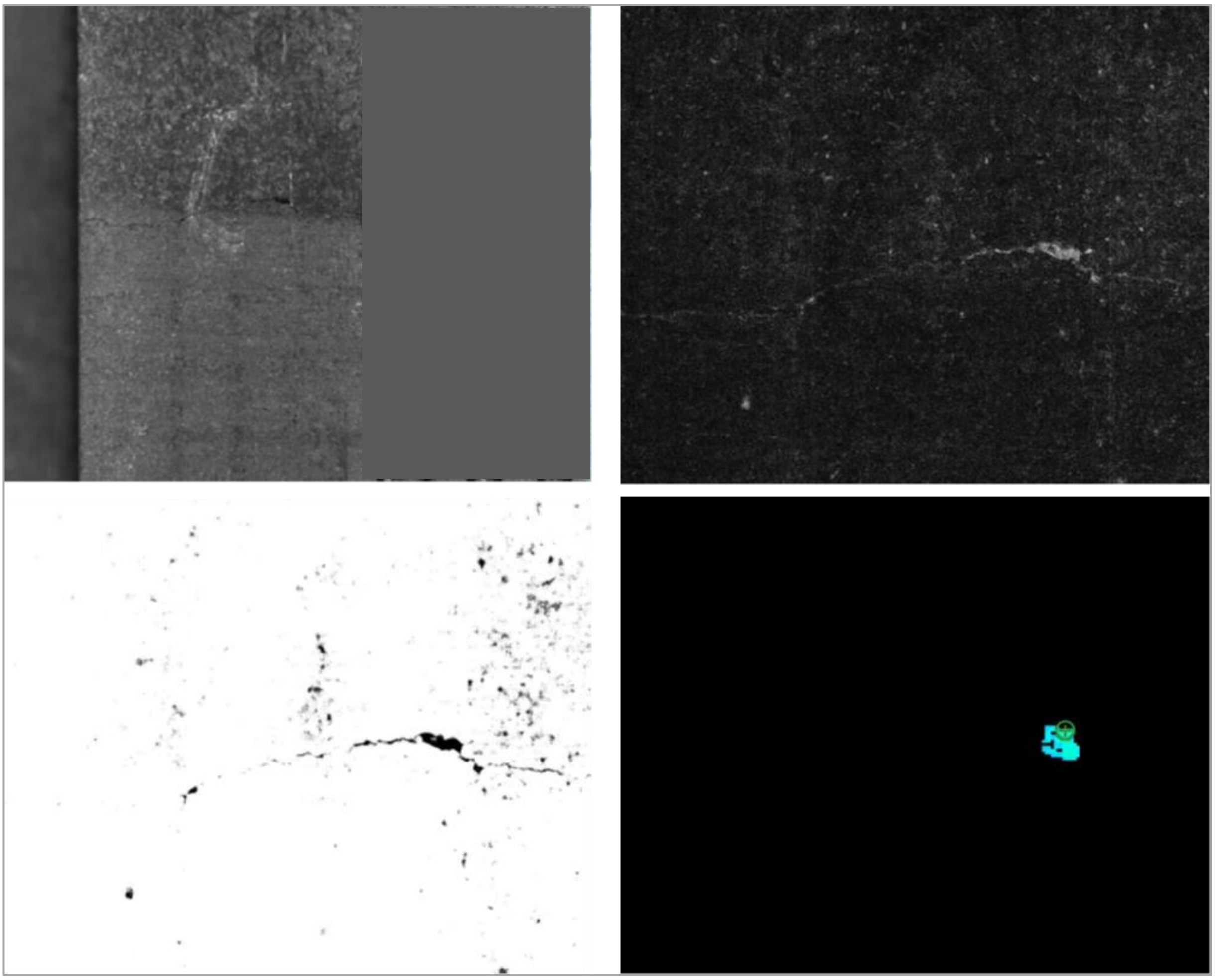

Figure 4: Upper left, a normal picture from a line scan camera; upper right, a magnified hair crack; bottom left, magnified hair crack after image processing using filters; bottom right, a hair crack (wider part) successfully detected.

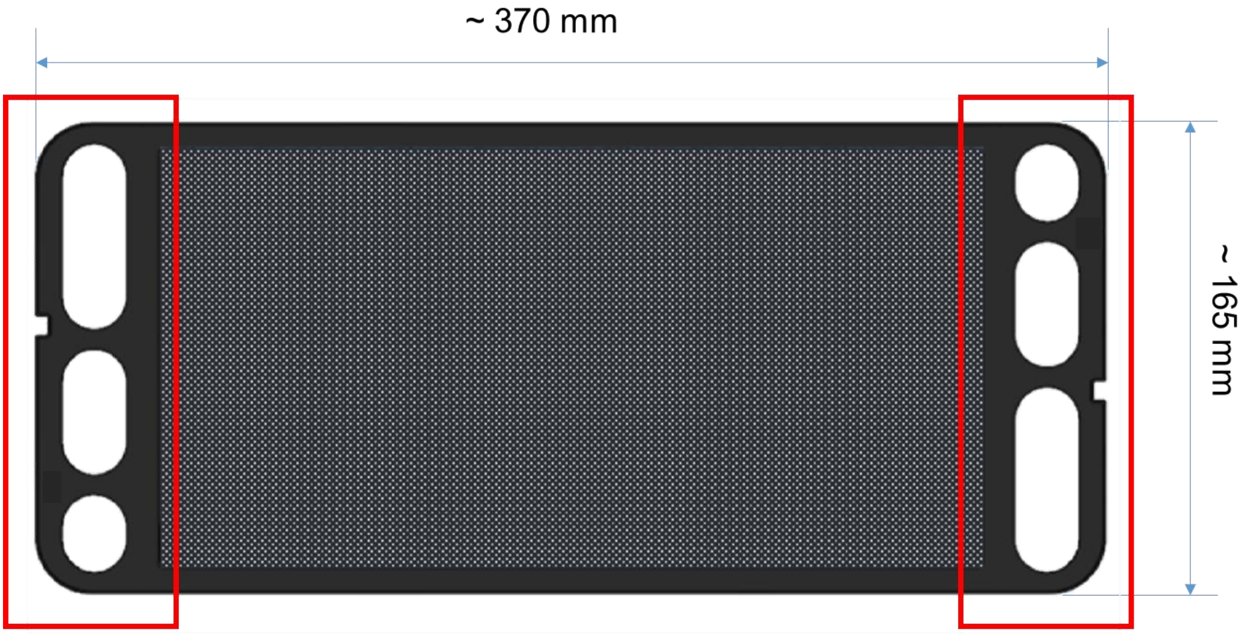

Figure 5: PM400 plate with marked surroundings of manifolds most susceptible to a hair crack formation.

4.2 MEA/CCM quality control

A series of QC methods was proposed as viable options for the QC of the CCM/MEA in the confidential report D5.1. The recommended method of MEA/CCM QC is the IR/DC active thermography (see Figure 6 and Figure 7) developed by the research team from National Renewable Energy Laboratory (NREL). [11] The method is not tied to any patent, it was developed in the scope of a publicly funded project. Therefore, it can be applied by anyone with a corresponding instrumentation available.

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.

For more detail regarding method's capabilities, capture and processing algorithms and pricing of the instrumentation, see the confidential reports D5.4, D5.1 (including the report's appendix) and the publications of the following literature sources [11; 12;13;14; 15].

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

[12] Aieta, N.V. et al.: Applying infrared thermography as a quality-control tool for the rapid detection of polymer-electrolyte-membrane-fuel-cell catalyst-layer-thickness variations. J. Power Sources 211, 2012, pp. 4-11.

[13] Ulsh, M. et al.: Challenges to High-Volume Production of Fuel Cell Materials: Quality Control. ECS Transactions 50.2, 2013, pp. 919-926.

[14] Bittinat, D.C. et al.: Defect Detection in Fuel Cell Gas Diffusion Electrodes Using Infrared Thermography. ECS Transactions 58.1, 2013, pp. 495-503.

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

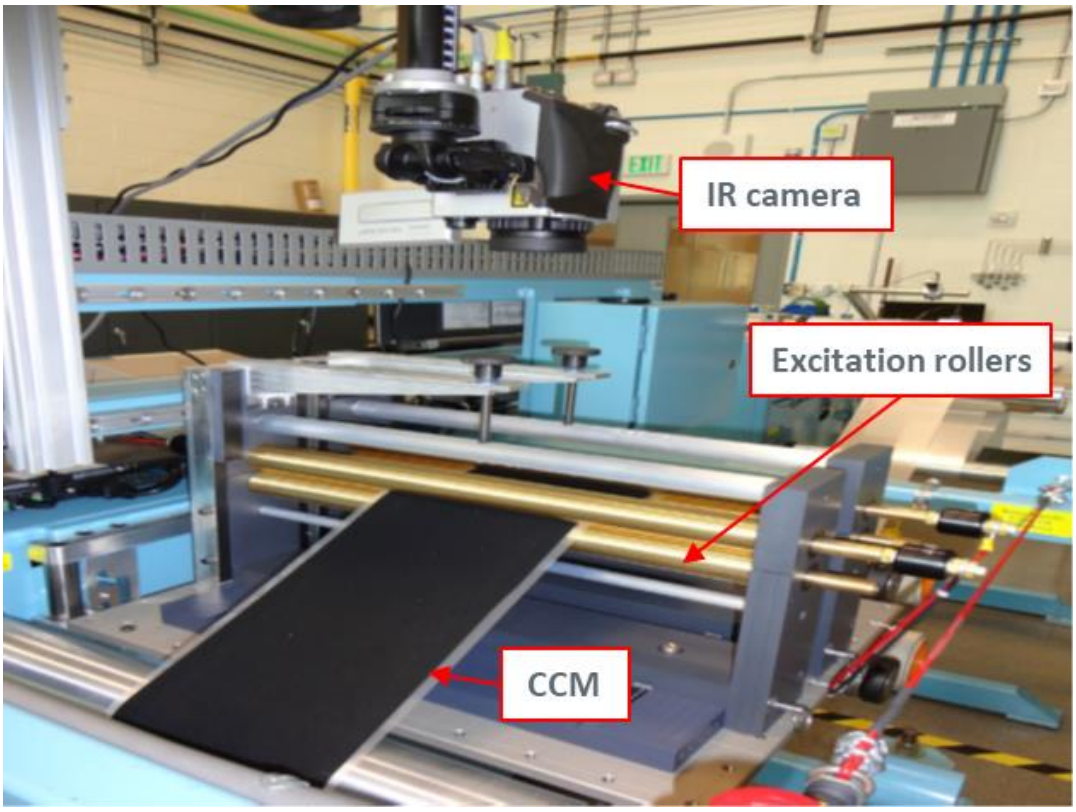

Figure 6: The setup used by NREL for an in-line IR/DC technique.

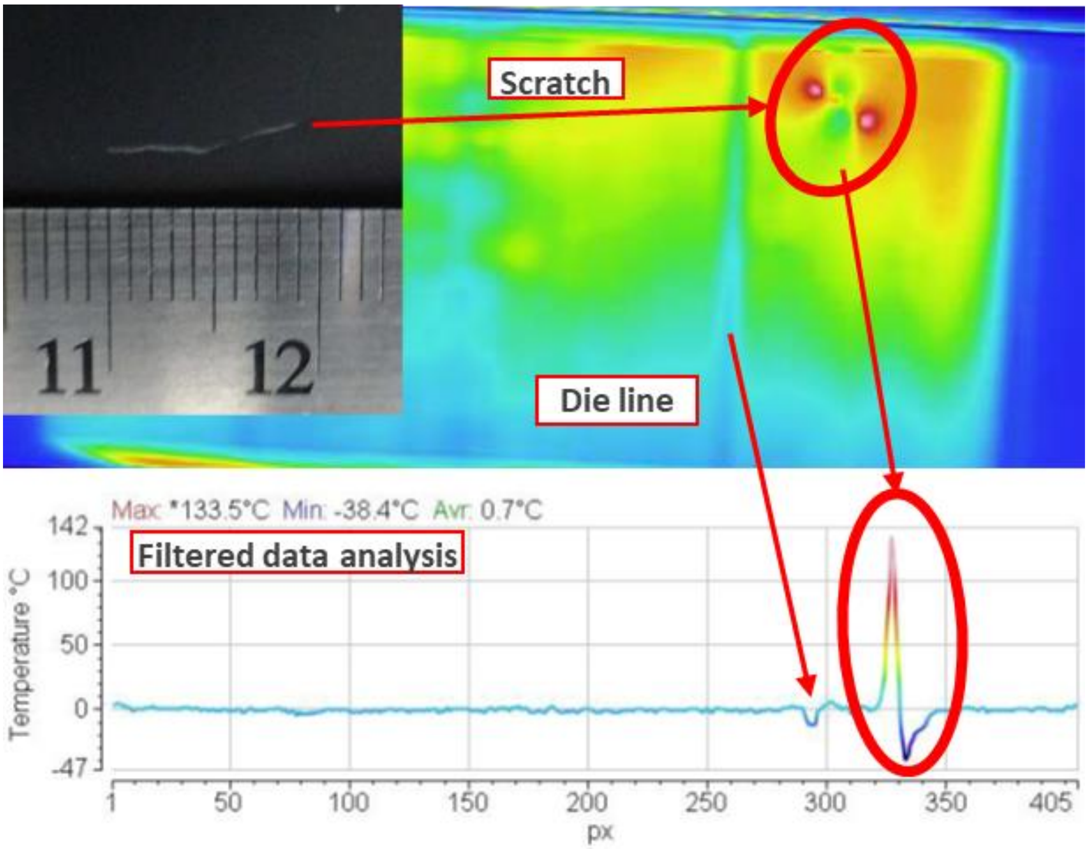

Figure 7: An example of defects (scratch and the "die line") detected using the in-line IR/DC technique.

4.3 Sealing quality control

The procedure of the investigation of the sealing quality by the 3D profiler was already extensively described in the confidential report D5.1. The scanning procedure is illustrated in Figure 8.

When using a dispensed sealing, the sensor can be mounted directly on the dispensing nozzle. Because only one small section of the sealing bead is scanned at a time, a model with a shorter *x*-range can be used. This allows using a model with faster frequency and better resolution. 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.

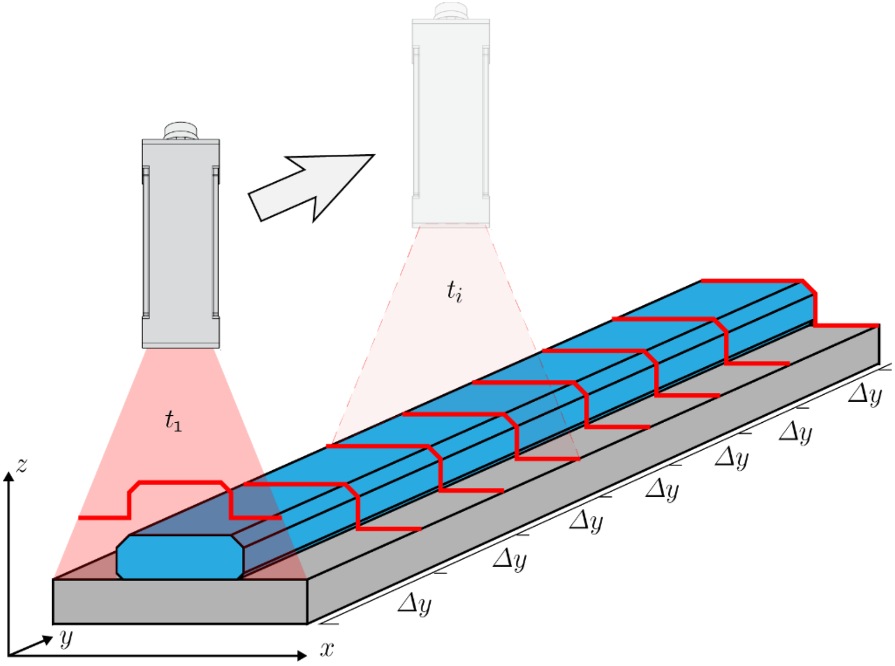

Figure 8: An illustration of the scanning process and collecting profiles (red) of the sealing bead (blue).

The sensor such as KEYENCE’s sensors working in-process (i.e., during the dispensing of the sealing – inline) in the LJ-V7000 series is sufficient for the 100-% inspection of the sealing bead in terms of width and height. A setup with a KEYENCE’s sensor would allow theoretical dispensing speeds of up to $v_{\mathrm{disp}} = 250$ mm/s (assuming non-transparent sealing bead, $\Delta y = 0.1$ mm, $N = 4$, $F = 10000$ Hz) which greatly exceeds the current dispensing speed of the PM’s dispensing robot.

However, a more rigorous testing with higher number of samples with sealing materials is required.

As already mentioned in the Section 3.3, a 1-% sample of the plates, i.e., every one-hundred plate, is recommended for a post-process testing (i.e., after dispensing and hardening of the sealing bead – offline) to detect possible deviations in width or height cause by hardening process.

For more detail regarding the testing of the sealing bead, see the confidential report D5.4 or its public version D5.6 (for selected information).

5 Conclusions

This report is a public version of the confidential report D5.3. A selected information is presented. For more details, see the confidential report D5.3 and the public report D5.6.

Currently, only QC implemented into the MMM is the vision system with the two cameras for positioning (for more details, see the confidential report D4.7). The quality-assurance protocols proposed in this report possess a potential of increasing the production reliability, reducing the scrap amount (i.e., number of reworked PEMFC stacks) and thus fulfilling the project's KPIs and targets set (see Table 1).

Table 1: Overview of the characteristics and KPIs for PEMFC stacks, the Fit-4-AMandA's targets and the baseline. [1;2]

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

Because the budget restrictions and the global pandemic limited the possible project's outcomes, the work will be continued outside the scope of the project. The proposed QC will be optimised in order to reduce the price as much as possible and then implemented into the MMM (either the one developed and build in the Fit-4-AMandA project or its possible successor).

6 Risk register

Table 2: Risk register.

Risk No.	What is the risk	Probability of risk occurrence	Effect of risk	Solutions to overcome the risk
1	Methods developed here will be not implemented in the next expansion stages in the MMM (principally due to several reasons possible)	Low	High	Full performance of the machine cannot be reached, high scrap rates will result →high accompanied costs
2	Other measurement methods that have not been investigated are becoming established on the market	Low	Medium	The new methods need to be investigated, assessed and adapted on the existing hardware →additional costs

7 Acknowledgement

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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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