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MANUFACTURING ENGINEERING

Production monitoring system development for manufacturing processes of photovoltaic modules

Pavel Tšukrejev*, Kaarel Kruuser, and Kristo Karjust

Department of Mechanical and Industrial Engineering of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

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Abstract. The main goal of the study is to develop the concept of the real time monitoring system for manufacturing processes of photovoltaic modules. Driven by reduced costs the solar power generation is growing rapidly and increases the number of photovoltaic modules being delivered to the customers. Automatic and early detection of defects/shortcomings reduces production costs and increases productivity. This paper is focused on detecting main issues, influencing performance of the manufacturing process of photovoltaic modules. Parameters that need to be monitored will be proposed in order to eliminate the faults. The main impact factors are analysed.

Key words: solar modules, photovoltaic process, real time monitoring process, smart sensors.

1. INTRODUCTION

The current study focuses on finding possibilities of monitoring the processes inside the photovoltaic modules during manufacturing process to see how changing some parameters can influence the quality of modules and how to use this information to make further predictions. The biggest challenges were real-time measurements of different parameters inside the module without destroying it.

2. GENERAL STRUCTURE AND MANUFACTURING PROCESS OF PHOTOVOLTAIC MODULES

The burning of fossil fuels has caused big part of atmospheric pollution and the greenhouse effect in general [1]. According to [2], the growth of photovoltaic (PV) capacity of the European countries (including Turkey) in 2017 was 28% higher compared to the year 2016. The main technology for manufacturing solar modules, with market share over 90%, is the silicon-based photovoltaic cells [3,4]. Fraunhofer ISE report notes that the efficiency of the silicon cells influences the laboratory efficiency depending on the used technology. Efficiency increases in case of monocrystalline or polycrystalline silicone 26.7% and 22.3%, respectively. The market efficiency is about 21.5%. Additionally, there are also other different perspective materials that can be used. One option is to use perovskite instead of crystalline silicon inside the solar cells, as it is considered to be cheaper material reaching the efficiency of 22.1% [5]. Another example of the future material that can be used as a solar cell is the black silicon, which has significant quantum efficiency (QE) over 90% [6]. The solar modules with silicon cells are consisting of different layers, composing a sandwich structure [7] shown in Fig. 1.

* Corresponding author, pavel.tsukrejev@taltech.ee

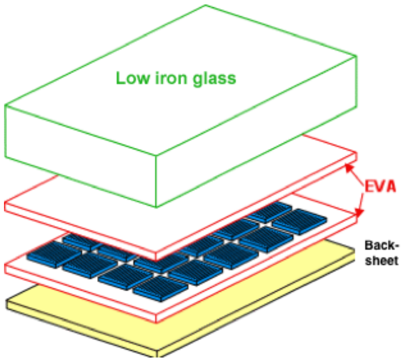

Fig. 1. Layers of solar module [8].

This paper addresses the manufacturing process of photovoltaic modules with silicon-based cells and focuses on the lamination part of it. The lamination step is essential for the manufacturing process. After lamination nothing can be changed as the whole module is already encapsulated.

3. MAIN ISSUES IN PHOTOVOLTAIC MODULES MANUFACTURING PROCESSES

As noted in [9,10], the major faults in solar modules are caused by wrong design or troubles during production. Main faults are as follows: air bubbles inside the modules; broken cells; micro cracks; hot spots; potential induced degradation (PID); snail trails. The photovoltaic modules production issues are analysed and the results are brought out in Table 1. It is explained how those types of issues and faults appear inside the module and what are the reasons. Certain suggestions, how it is possible to overcome these issues, are proposed in the last column of Table 1.

Understanding the nature of those faults helps to follow the set of selected parameters in order to prevent the issues listed above. Most of the issues in photovoltaic modules appear during lamination process. This process is very important for successful production of modules but very complicated to be tuned. Setting depends on used materials. Laminator has to perform

Table 1. Different issues in photovoltaic modules

Issue	How does it look like in the product	Why is it bad?	What is causing it?	How to avoid it?
Air bubbles	Bubbles are laminated inside the module – in different spots.	Bubbles can cause delamination. Impossible to repair.	1. Trapped air. 2. Fumes of EVA (ethylene-vinyl acetate). 3. Cooling process [9].	Fine tuning of lamination cycle is the only possibility to avoid bubbles.
Broken cells	Cells are broken inside the laminated module. Either there is a crack or a whole piece of cell is apart.	Can impact power performance. Cannot be repaired.	1. Micro cracks in cells. 2. Transportation issues. 3. Production handling. 4. Issues in production process itself.	Ensuring that handling during manufacturing and processing would not damage cells.
Micro cracks	Not visible to the eye. The crack does not penetrate the whole cell (ca 200 micrometers).	Can impact performance of cell. Risk of a real crack. Growing due to the weather influence.	1. Transportation issues. 2. Supplier ships faulty cells. 3. Wrong handling during production.	Making electroluminescent picture of every single cell that is going to be used in production.
Hot spots	The burnt spot under the glass on the surface of cell.	Spots that become warmer inside the module, leading to short circuit.	Issues in soldering the ribbon to cell. Structural defects of cell.	Ensuring the quality of soldering interconnectors.
PID	Cannot be visually determined.	Accelerated aging of modules. Solar modules could lose performance.	Potential difference between solar module and the earthing.	Improving design of the module and the choice of materials used.
Snail trails	“Browning” of contact fingers of cell in a form of trails. Appears after some years.	Appearance of module. Can cause loss in power output.	Moisture penetrating the module causing oxidation of the components of cells on the trails of micro cracks.	Avoiding different types of cracks in cells.

the whole cycle (up to 25 minutes) in order to produce a module. During lamination the chamber is closed and it is not possible to see if something is going wrong there. After every change in the program it is important to wait the whole cycle. In case of wrong settings modules will be scrapped.

There are different steps in lamination process with different temperatures and pressures. The encapsulant material EVA becomes liquid during lamination. This may influence cells to float inside and cause undesirable displacements. During the lamination EVA transforms and forms a polymeric connection inside itself.

3.1. Measurable parameters

The study of lamination process allows selecting the parameters that need to be tracked:

- *pressure (input)* – essential during lamination process (impact on the quality of encapsulant and appearing of air bubbles);
- *temperature (input)* – main parameter for photovoltaic module lamination. Impacting the quality of encapsulant;
- *duration (input)* – lamination time. Influences the content of EVA gel and bubbles inside the laminate;
- *displacements (output)* – is essential to understand if module's structure is right. Finding displacements which are not visible to the eye and understanding why they occurred helps to improve modules in general;
- *content of EVA gel (output)* – important parameter to be followed but hard to be tracked by sensors in real time, as it is determined during chemical processes;
- *cracks (output)* – finding different types of cracks before laminating process allows to replace the cell;
- *measured temperature (temporary output)* – installation of additional sensors to collect data about the temperature should be considered as it could help making decisions how to measure temperature in a right way. Figure 3 shows the experimental setup of photovoltaic module with thermal sensors installed on the top of the module.

In order to track those parameters, the main idea is to embed a sensor inside the photovoltaic module body in the stage of production. Embedded sensors inside the composite materials was studied by Herranen et al., in [12] and the optimal shape for sensor's protective housing was proposed. The optimization procedure based on combining hybrid genetic algorithm (HGA), artificial neural networks (ANN) and reduced-order models (ROMs) [13–17], was adapted for optimal design of housing of the electronic component.

4. DEVELOPING THE CONCEPT OF MONITORING METHOD FOR PRODUCTION OF PHOTOVOLTAIC MODULES

The real-life production monitoring stands for continuous checking of parameters from the manufacturing object [18, 19]. This could be a powerful tool for measuring necessary parameters and understanding what is happening inside the product during the manufacturing process. There is possibility to use different types of sensors, which could be embedded inside the photovoltaic module, e.g., RFID (radio-frequency identification) sensors [11].

Before monitoring the manufacturing process of photovoltaic modules, it is necessary to identify important parameters that need to be monitored during production process. In other words, key performance indicators (KPIs) will have to be defined for using enterprise analyses model (EAM) [20–24].

The KPIs should be related to two main fields: jobs and courses and cover different areas like machinery, materials, processes, employees, facility, products, production order, etc.

4.1. Basic concept of monitoring system for photovoltaic modules

There is a number of approaches and requirements for the production monitoring systems. Let us proceed with the basic concept of production monitoring system developed by the workgroup in [18] and shown in Fig. 2.

This concept is proposed for particular case study with additional measurable parameters like pressure, temperature, and duration. This system can be adapted to the manufacturing process of photovoltaic modules with some changes. The concept proposed for production monitoring system integrates the following five main modules: data collection, analysis, visualization, storage, and security. The sensor system is collecting different data (ambient temperature, pressure, duration, displacements, and electroluminescence) from workstations. The storing, computations and analyses are made in the server or cloud side; and integration between the monitoring system and enterprise resource planning (ERP) system is developed. The collected information is sent to the ERP system where it is visualized.

4.2. Tests of temperature measurement

As noted above the lamination temperature has impact on quality of encapsulant and can be considered as key factor in lamination process. In order to validate the

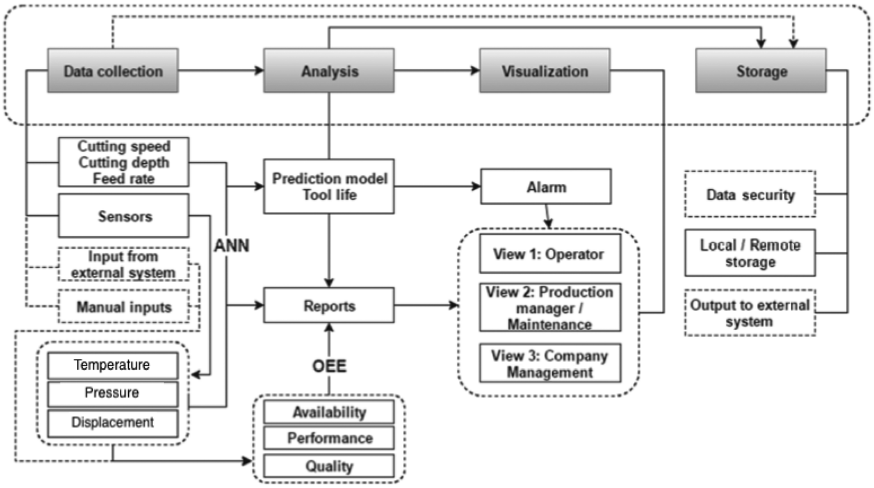

Fig. 2. Concept of the production monitoring system [18].

concept of measuring parameters inside the laminating chamber the temperature measurement was performed. The thermometer TES 1312A with two wired temperature sensors was employed. Sensors were installed on the back of solar module attached to the backsheet. Placing of thermal sensors can be seen in Fig. 3.

There were three tests performed: (1) usual lamination program with temperature of 144 °C; (2) program with increased temperature of 150 °C; (3) program with reduced temperature of 130 °C. The results of tests and gathered temperature data are represented in Table 2 and Fig. 4. Two measured values of temperature (Temp. 1 and Temp. 2 in Table 2) can be considered as an output from particular temperature test. The temperature was checked and registered with time stamp and values of

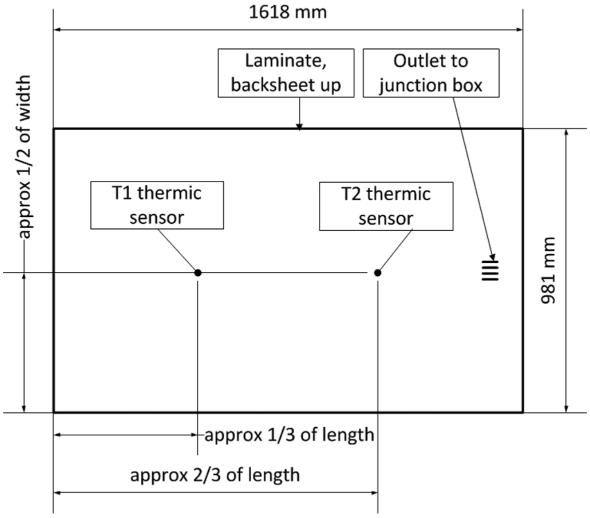

Fig. 3. Schematic representation of experimental setup.

measured temperatures. The set value of the temperature is known from laminator receipt and is given also in Table 2. "Machine values" are the values that are either set by receipt or measured by machine, not by experimental setup.

Gathered results show that there is a difference in set and real temperatures. The reason is the fact that heating element of the machine with temperature sensor is located underneath the heating plate. The module is located on the heating plate and the thermal sensor used in the test was set on the top of the module, so the whole structure of the module is between two sensors. Surface temperature of the module never reached program receipt value by the end of lamination cycle in any of tests. One important remark is that wired sensors were used in experimental set-up and wires had left traces on the surface of the backsheet. This means that particular module was defined faulty and was scrapped. Wireless solution or other type of wires should be used.

In Fig. 4, temperature measurement results from Table 2 are presented according to performed test number (the first number) and sensor position (decimal number). Measurements were performed five times.

5. CONCLUSIONS

It is essential to understand, what is happening inside the modules during production as well as to react fast to aoid faults in products. This kind of data gathering and reacting to the results of analysis will help to improve overall quality of products as well as understand what is happening inside the modules during different stages of production.

Table 2. Results of the tests

Measure-ment	Time from start	Machine values				Measured	
		Set temp., °C	Measured temp. value, °C	Set pressure, mbar	Meaured pressure, mbar	Temp. 1, °C	Temp. 2, °C
1.1	2 min 47 s	144	143	–1000	–1024	60.3	68.7
1.2	6 min 42 s	143	142	–300	–303	95.6	99.3
1.3	10 min 4 s	143	143	–300	–293	117.8	119.1
1.4	14 min 22 s	143	143	–300	–289	130.3	130.7
1.5	14 min 54 s	144	143	0	–2	131.1	130.9
2.1	2 min 44 s	150	149	–1000	–1006	51.7	57.5
2.2	6 min 16 s	150	148	–300	–310	80.9	87.2
2.3	10 min 1 s	150	150	–300	–300	117.4	118.1
2.4	14 min 31 s	150	150	–300	–307	134.5	134.4
2.5	15 min 00 s	150	150	0	7	134.4	135.8
3.1	2 min 34 s	130	130	–1000	–1013	36.0	32.9
3.2	6 min 01 s	130	129	–300	–361	71.4	74.7
3.3	10 min 5 s	130	130	–300	–320	100.2	103.3
3.4	14 min 35 s	130	130	–300	–300	118.7	120.5
3.5	15 min 00 s	150	150	0	7	134.4	135.8

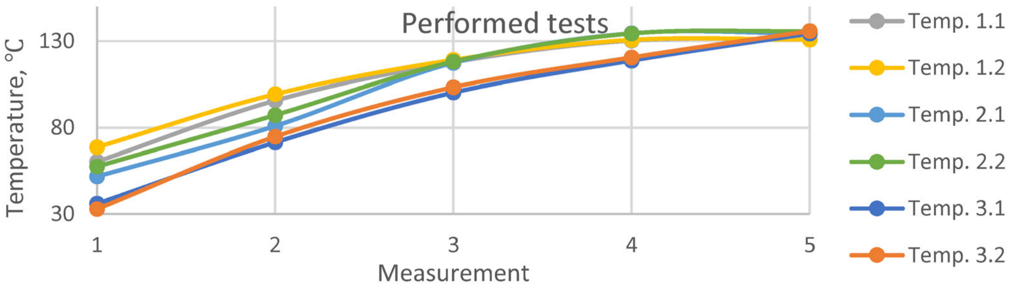

Fig. 4. Temperature test results in different positions and input data.

In the current paper, the main issues and their sources have been pointed out. The concept for production monitoring system is proposed. The real time tests for measuring set temperature and temperatures in two additional nodes are performed and the results are analysed. Further studies will be performed regarding embedding sensors into solar modules.

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Tootmise seiresüsteemi arendamine fotoelektriliste moodulite tootmisprotsesside jaoks

Pavel Tšukrejev, Kaarel Kruuser ja Kristo Karjust

Fotoelektriliste moodulite tootmise seiresüsteemi väljaarendamiseks on läbi viidud uuring põhilistest kvaliteediprobleemidest, mis võivad tekkida moodulite valmistamise käigus. Uuringust selgus, et enamik probleeme tekib lamineerimise etapi jooksul. Tehti kindlaks põhjused, mis viivad kvaliteediprobleemide tekkimiseni. Põhjuste alusel on koostatud loend parameetritest ja mõjufaktoritest, mida on vaja lamineerimisel jälgida. Üldine tööpõhimõte seiresüsteemi arendamisel on integreerida moodulisse andurid, teha mõõtmised ja edastada tulemused serverisse. Saadud andmete põhjal saab teostada analüüsi, prognoosi ja visualiseerimist.