TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Material Science

ADHESIVE INTEGRATION OF PHOTOVOLTAIC MODULES ON METAL BUILDING MATERIALS

ADHESIIVNE PÄIKESEPANELIDE INTEGREERIMINE METALLIST EHITUSMATERJALIDEGA

MASTER THESIS

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Tallinn, 2018

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Department of Material Science

THESIS TASK

Student: Sergii Akhinko, 165545KAYM(name, student code)

Study programme: KAYM, Materials and Processes of Sustainable Energetics (code and title)

main speciality: Processes of Sustainable energetics

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Thesis topic:

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(in Estonian) ADHESIIVNE PÄIKESEPANELIDE INTEGREERIMINE METALLIST EHITUSMATERJALIDEGA

Thesis main objectives:

1. Explain potential advantages of proposed assembly method.
2. Prepare and perform experiments to define level of reliability of the structure.
3. Estimate scope of application and further testing if required.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	To perform literature review on the given topic	30.03.2018
2.	Prepare required materials and perform experiments	04.05.2018
3.	Describe experiments in detail and prepare report on results	24.05.2018

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CONTENTS

PREFACE

This research was carried out at the Department of Materials Science. Author is grateful to the financial support from the Archimedes Foundation under the Dora plus scholarship grant and School of Engineering for granting Specialty and Performance based scholarships.

Thesis topic was initiated by my supervisor Andri Jagomagi. All experiments were carried out on the company's (Roofit Solar) production site. All the materials required for experiments were provided by Roofit solar.

I would like to express my gratitude to all my colleagues for the contribution to this work. My special thanks go to the following people:

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List of abbreviations and symbols

CdTe	Cadmium Telluride
a-Si	Amorphous silicon
BIPV	Building integrated photovoltaic module
EVA	Ethylene vinyl acetate
PV	Photovoltaic module
I	Current
V	Voltage
R	Resistance
FF	Fill factor
I-V	Current-Voltage characteristics
P	Power
A	Area
Ag	Silver
POE	Polyolefin
PET	Polyethylene terephthalate
PVF	Polyvinyl fluoride
PVDF	Polyvinylidene fluoride
WVTR	Water Vapor Transmission Rate
T_g	Glass temperature
PP	Polypropylene
FFP	Fiber fortified plastic
MMA	Methyl methacrylate

INTRODUCTION

Photovoltaic cell is a device that transforms solar radiation into electricity with the help of phenomena called “photovoltaic effect”. It was discovered in 1839 and that was the starting point for development of photovoltaic systems. Solar cells produce electricity without noise pollution and relatively easy in construction having no moving parts. The sun delivers on Earth the amount of energy that mankind consumes in a year. In addition, it is most abundant, clean and endless energy source. Nowadays, when the world facing challenges such as global warming, pollution and other effects, which aggravates our ecosystem, it is very important to make efficient use of sustainable energy sources.

Utilization of renewable energy sources gradually rises, since technology becoming cost competitive with fossil fuels. New technological advancements expand use of renewables in deferent industries. An example of this are European countries, which introduce programs for full transition to renewable energy production. Currently, Denmark produces more than enough of electricity to cover country’s demand and sell surplus to neighboring countries. Estimated renewable energy share in total energy consumption is accounted for 19% at the end of 2016 [1]. Solar photovoltaics holds only a small portion of renewable energy production. However, it is the fastest growing sector, mainly due to introduction of very effective incentives in China. The country takes leading positions in production of electricity from PVs and at the same time largest production of photovoltaic modules also located there.

Solar cells technologies are usually divided into three generations. First generation cells mainly consist of crystalline silicon wafers and demonstrate commercial efficiency in range 15-20%. Among the advantages of this type is their high stability and good performance. Second generation cells are referred to thin film photovoltaics usually made from CdTe and a-Si. The idea behind is to reduce production costs due to low material consumption. However, expensive technological processes are present in production, which serves as a limiting factor in price reduction. Thin films may be flexible, thus can be applied on curve surfaces. Third generation represented by solar cells utilizing organic material and multi-junction solar cells. Last are able to reach 40 % efficiency due to their composition of cells with different band gaps, however they are very expensive and usually applied in space industry. Polymer solar cells are low cost and easy to manufacture, but have low stability. Perovskite solar cells is a new type with great potential of more than 20% is under research [2].

With development in photovoltaic technologies prices for PV modules significantly drop during past decades. That brings photovoltaics to a new level from large solar power stations to household applications for ordinary people. According to statistical data, about 25% of energy in residential sector is accounted for electricity [3]. Firstly, PV modules were applied directly to the roof top with the help of metallic structures. However, this approach is not attractive for consumers due to aesthetic reasons. In addition, purchasing PV system separately from roof is expensive. BIPV is a modern solution for buildings that consist of solar cells incorporated into rooftop material by means of lamination or adhesive connection. It serves as construction material and power generation system at the same time. The simplest BIPV system consist of array of modules and inverter connected to grid. During day time when the sun is shining, modules convert solar radiation into electricity. Part of this electricity is consumed by building and surplus is usually sold to the grid. At night, electricity is supplied from grid. There are also exist so called off-grid systems, additionally equipped with batteries, that accumulate electricity during day period and release it at night. Such systems enables to have electricity all the time, independently from grid and usually utilized for remote households [4].

BIPV modules have a variety placing possibilities in buildings, such as roof, facades and glazing. Present work is concentrated on adhesive connection of PV module to rooftop material, particularly metal sheet. Generally, BIPV modules are fabricated using two glass panes and encapsulated material between them, such as EVA. These types of modules usually installed on the roof with the help of supporting structures (flat roof case) or over roof material. However, with the development of BIPV industry different design solutions have been proposed. The one, currently used by author is PV module connected to metal sheet, initially by laminating. However, this process requires modification in production line, because of using metal sheet as a backside of the module. For small companies, development of automatic production line is not economically efficient and using small scale equipment takes a lot of time for production. Therefore, there is a need to develop another method of assembling for BIPV module.

Since, production technology for regular modules is quite mature and flexible, modules can be manufactured to customer requirements. The idea is to divide BIPV module production by two parts. One part, regular PV module with some design modifications is ordered from one company and roof material, metal sheet is supplied by another company. Connection of two parts should be tested with different adhesives. The problem to be solved is to avoid trapping of oxygen between the interfacial layer and module parts, since it may negatively affect module operation and reduce its life time. In addition, mechanical tests required to determine BIPV reliability.

1. Theoretical information and literature review

1.1 Development of photovoltaics

A solar cell is an electrical device that converts energy of light directly into electricity by the photovoltaic effect, which is a property of semiconductors. This effect was first discovered by French scientist A. E. Becquerel in 1839. Later, in 1884 Charles Fritts successfully created first solar that consisted from layer of selenium covered with thin film of gold. The modern history of photovoltaics started in Bell labs where researchers accidentally discovered that pn junction diodes are able to generate voltage under exposure to light [5]. Since that time many researchers concentrated their efforts to achieve higher efficiency and develop new materials that can be used in photovoltaics. At the end of twentieth century industries became more mature in this field. New manufacturing facilities were opened in Japan, USA and Europe. Production costs were decreasing with development of new technologies.

Nowadays, because of introduction of new incentives for photovoltaics in national policies, China dominating on the global production market. Most of the photovoltaic installations are located in China, Japan and USA. European market has decreased during past years. Leading positions in Europe holds United Kingdom followed by Germany. In 2016 total installed capacity of photovoltaic modules was about 303 GWp. In addition, new installations had approximate capacity of 75 GWp with almost equal distribution between rooftop installations and centralized power stations [1], Figure 1.1.

Another factor, that drives development of photovoltaics is growing concerns about climate change. Global warming became one of the main topic discussed around the globe. As an example serves Paris climate agreement in 2015, according to which each country that signed the agreement should develop plans and produce reports to mitigate global warming. This led to huge investments into deferent areas of Sustainable energetics and introduction of feed in tariffs.

BIPV market is considered as an expensive in Europe. One of the main driver of its development is legislation for Nearly Zero Energy Buildings. In order to expand BIPV market, there are several challenges that to be overcome. Generally, BIPV modules lack flexibility in design and are not aesthetical attractive both for customers and architects. Moreover, modules should demonstrate long term stability and performance plus comply with industry standards. One of the projects aimed to solve this issues and move BIPVs to global market is PVSITES. Work scope of the project is to create a set of technologies, systems and application to satisfy market requirements.

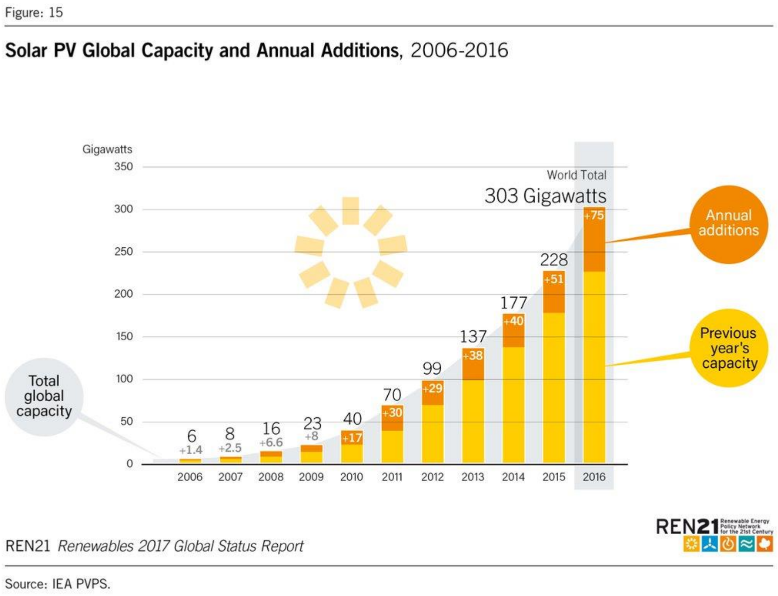


Fig. 1.1 Global annual photovoltaic capacity and growth

1.2. Doping of semiconductors

Semiconductors itself are not stable conductors of electricity. In their pure state they refer to intrinsic semiconductors means that material has crystal lattice defects, such as vacancies. In this case their behavior changes from insulator like at low temperatures to conductors when sufficient energy is applied. Extrinsic semiconductors created by adding atoms of different chemical element into the initial semiconductor. The process known as doping. Introduction of donor atom with extra electrons, such as phosphorus results in n-doping. Alternatively, addition of acceptor atom with less electrons, for example boron, outcome in p-doping [7].

1.3 The p-n junction

The p-n junction is considered as a fundamental part of semiconductor technology. It is formed when p-doped and n- doped materials are joined together. Near the interface, free holes from p-type material start to penetrate into n-doped part, leaving behind an area that is negatively charged. On the other hand, electrons from n-type migrate to p-side, leaving behind the area that is positively charged. This inter diffusion process results into forming of depletion region near the interface illustrated in Figure 1.2. A strong electric field is generated, that transforms p-n junction into a diode, a device that conducts electricity only into one direction. Energy band diagram for p-n junction is demonstrated in Figure 1.3.

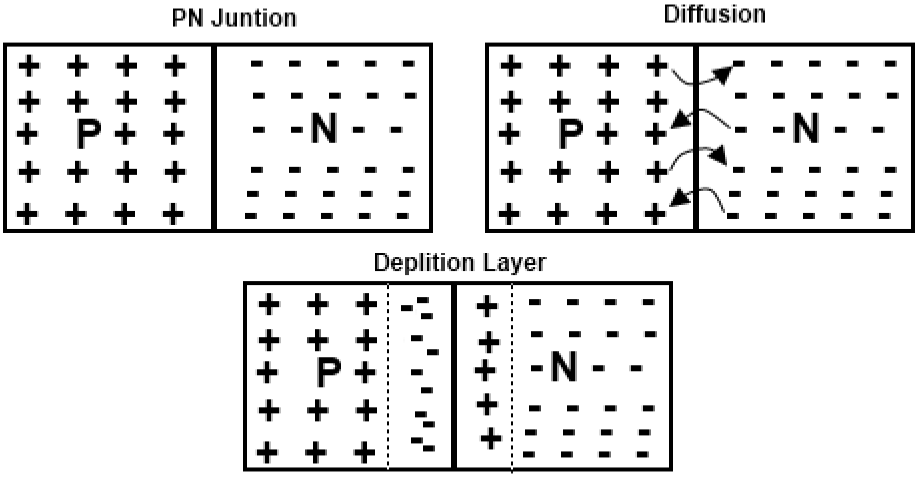


Fig. 2.2 Global annual photovoltaic capacity and growth

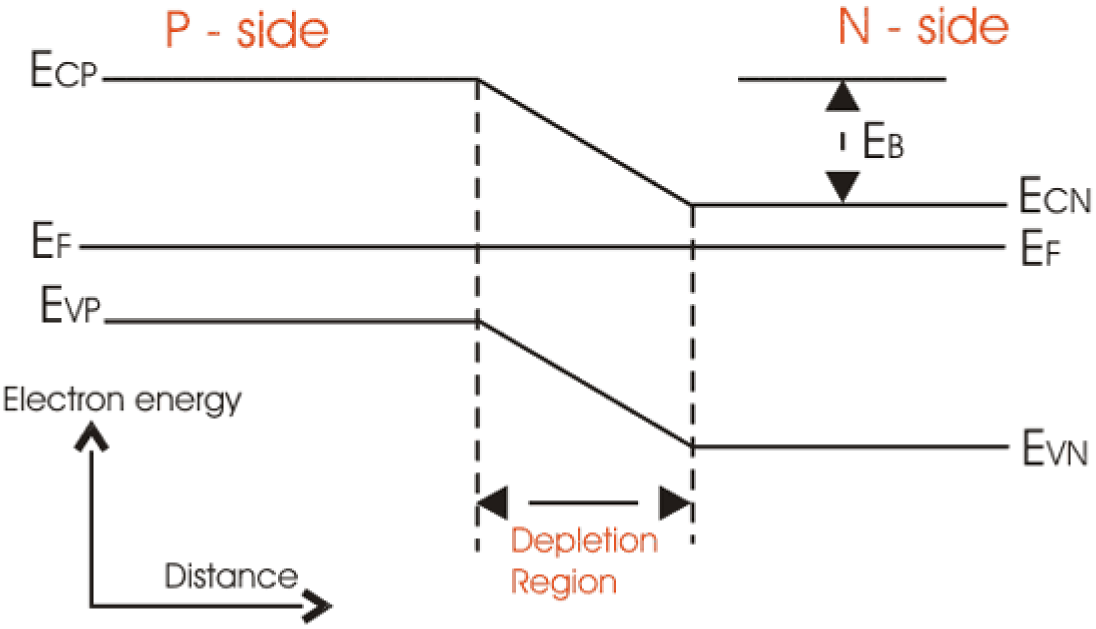


Fig. 1.3. Energy band diagram for p-n junction.

1.4 Electrical characteristics

Solar cell itself represent a simple diode, thus equations that describe diode characteristics are applicable. Shockley diode equation represent voltage – current characteristics for ideal diode for forward or reversed bias 1.1 [9].

$$I_d = I_s(e^{\frac{qV_D}{kT}} - 1), \tag{1.1}$$

where I (A) is a diode current, I_s (A) is saturation current, V_D is a current applied to diode. kT is energy consisting of Boltzmann constant, k, and room temperature, T (K), and q is an electron charge.

A Simplified circuit diagram for solar cell that consist of a current source connected in parallel to the diode and shunt resistor R_{sh} is shown in Figure 1.4.

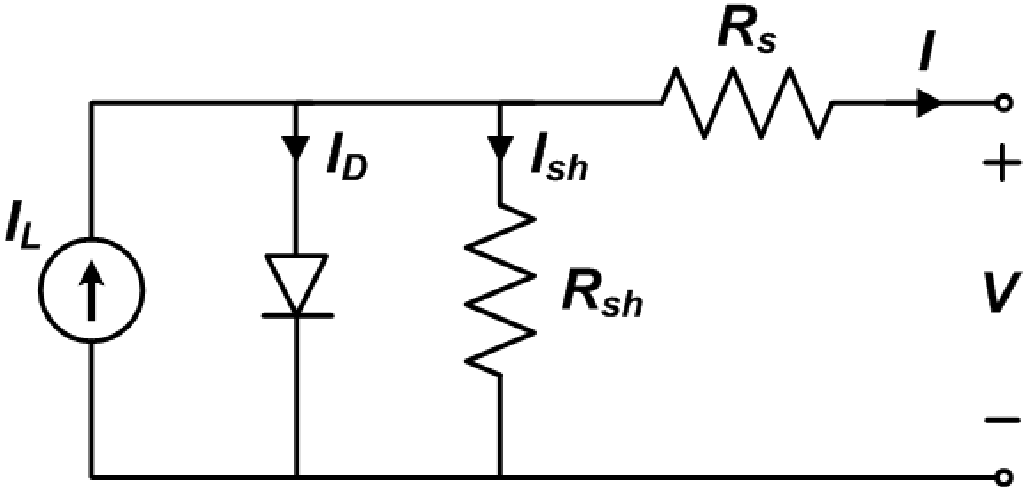


Fig. 1.4. Equivalent simplified circuit for solar cell

I_L is a current generated by solar radiation that flows to the output. I_D is a diode current described by equation 1.1. When current is generated by light, it flows to the output, with distribution between parallel elements of the circuit. Therefore, relationship between current and voltage for solar cell circuit is demonstrated in formula 1.2.

$$I = I_L - I_d - \frac{V+IR_s}{R_{sh}} = I_L - I_d - I_{sh}, \tag{1.2}$$

where I and V are current and voltage of the circuit respectively.

Maximum solar cell current I_{sc} can be measured with shirt circuit, when voltage is equal to zero. Alternatively, When the circuit is open, output current is equal to zero and maximum voltage can be measured V_{oc}. Another important parameter for solar cell characteristics is FF. It is determined using maximum power point of the solar cell, which is described by V_{mp} and I_{mp}. These parameters are optimized during the production stage to reach maximum efficiency. Figure 1.5 is an example of (I-V) curve and demonstrates above mentioned characteristics [10].

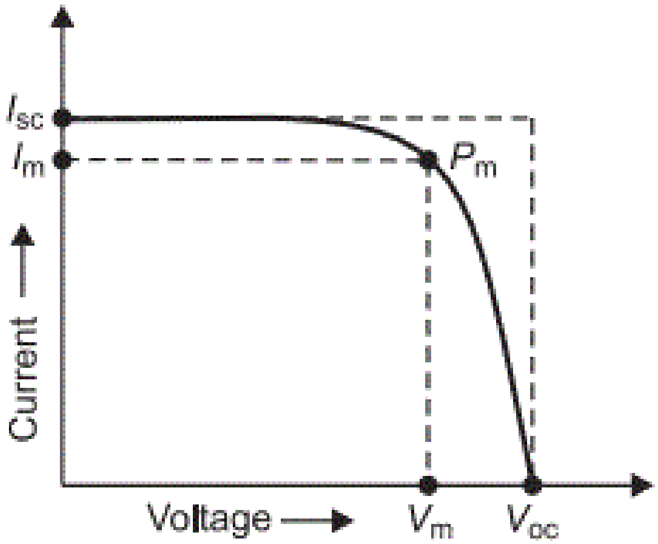


Fig. 1.5. Typical (I-V) curve with ideal parameters.

Fill factor is determined as a ratio between measured power and its theoretical value (ratio between area generated by V_m x I_m, and rectangle I_{sc} x V_{oc}).

$$FF = \frac{\mathrm{Vm} \times \mathrm{Im}}{\mathrm{Isc} \times \mathrm{Voc}} \tag{1.3}$$

Maximum power is calculated:

$$P_m = \mathrm{Isc} \times \mathrm{Voc} \times \mathrm{FF} \tag{1.4}$$

Finally, cell efficiency is determined as:

$$\eta = \frac{P_m}{P_{in}} = \frac{P_m}{E \times A_{cell}}, \tag{1.5}$$

where E is input irradiation and A_{cell} is area of solar cell.

1.5 Structure and fabrication of photovoltaic module

Power of a single photovoltaic cell is too small to make a practical generator; thus several cells should be connected in order to improve power Figure 1.6. Such connection is known as a photovoltaic module. It can be purchased in the market to build real PV power plants. Lifetime and performance of the module depend on the fabrication method offered by producer, where the most important parts are encapsulation and protection.

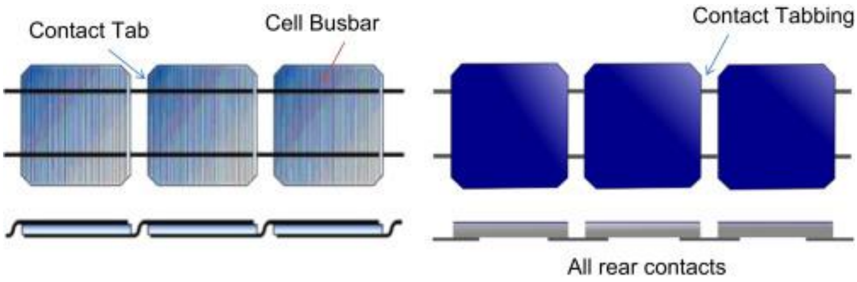


Figure 1.6. Solar cell interconnection [12].

In general, fabrication of PV module was developed several decades ago and is still in use by most of the producers. In order to produce modules for specific applications such as building integration or marine application, several changes in production process are required [5].

1.5.1 Cell arrangement

Typically, cells in the module are connected in series, with copper ribbons as a connection material. Cells are usually covered with blue anti-reflection coating to reduce reflection from the surface. There are also other colors available for coating, however they reduce efficiency of solar cells approximately on 20 % [11]. Since they absorb part of the solar spectrum. For building integration, when choosing color of the cell, there is always trade between aesthetic design and efficiency.

Tabs have 100 to 200 µm thickness and coated with alloy of 96,5 % and 3,5 % Ag. They are sold by flame, IR, hot air, Laser or eddy current [15]. Tabs from the front side of one cell join with the back side of adjacent cell, forming a string Figure 1.6. Number of individual solar cells in modern modules vary between 24 to 48. It is important that tabs overlap a long distance on the next cell, because conductance of printed bus bars is to too low. bars is too low. Two (or three for larger cells) tabs per cell are employed, thus providing redundancy which allows current to flow in case electrical continuity is broken due to some failure [13]. In addition, tabs form non-rigid connection between cells, which enables to avoid damage because of thermal expansion.

Tabs connect to solar cells by soldering in two steps: first, they are connected to one side of the cell, then to another. During this process, bending of solar cell may occur due to difference of thermal expansion coefficient between silicon and copper Fig. 1.7. This may cause increased breakage of solar cell during next soldering step or during the lamination process. In addition, difference in temperature of solar cells themselves and soldering process may cause microcracks. Consequently, it is important to reduce temperature fluctuations by attachment of both tabs simultaneously. Moreover, in order to reduce possibility of microcracking heating plate is utilized. Before start of soldering process solar cells are placed on a heating plate and wait until they heat up.

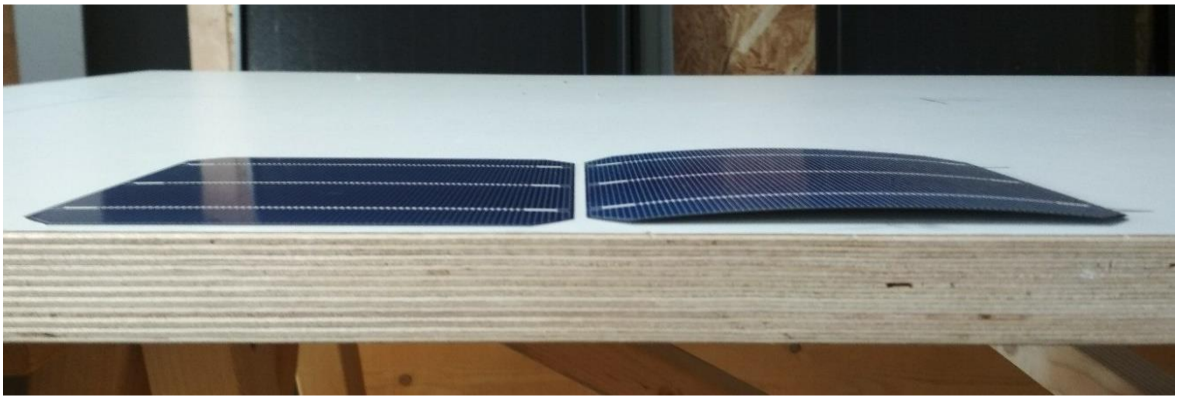


Fig. 1.7 Difference in thermal expansion results in bending of solar cell.
Before and after soldering.

Strings are connected in the module with the help of auxiliary ribbons. In addition, bypass diodes connected to general scheme to avoid shading consequences or module failure.

1.5.2 Structure of the module

In order to provide reliable and stable operation of over 25 years in outdoor conditions, array of cells should be properly laminated and protected. Module should withstand different mechanical loads, protected from humidity and properly isolated to ensure safety for people.

Top cover of the module is a glass with high transmission in the wavelengths which can be used by the solar cells, usually in the range of 350 nm to 1200 nm [14]. In addition, the glass should have low iron content, otherwise light transmission will be reduced. Moreover, to improve load resistance and ensure safety in case of module breakage, tempered glass must be used.

Furthermore, glass should be stable under long exposure to UV and have good self-cleaning properties. It is important to mention that in order to reduce reflection from glass surface, texturing is applied. However, advantages of textured glass are usually annihilated by adhering of dust and dirt to the glass, since it reduces self-cleaning properties. Typically, low-iron glass is used as it has all the mentioned properties. Plus, it is most stable and trouble-free component of the whole module parts.

Cell array is enclosed between two layers of encapsulated material. The encapsulant should be stable at defined range of temperatures and under long UV exposure. In addition, it should be transparent and has low thermal resistance. Curing time is also important property of encapsulant, since it directly influences on the production time of the module. Usually, EVA is utilized for this purpose, because it has all required properties plus it is a mature technology. However, for this project POE is used. It has all of the advantages of EVA plus improved resistance to moisture, which makes it more stable in humid climate.

Back sheet of PV module is used to protect it from external loads, moisture and ensure proper isolation. Typically, it is made of three layers. Outer layer is Tedlar®, which acts as a good barrier against moisture, however it does not provide proper isolation against high voltage. Thus, second layer made of polyester is used. The last layer is Tedlar® or EVA connected to polyester. Nowadays, there are other different materials, used as a back sheet available on the market. Such materials as PET, PVF, PVDF step by step substitute EVA, since they provide better properties. One of the example is WVTR of PET is ten times lower than EVA, which is very important for humid environment. Typical module structure is presented on Fig. 1.8.

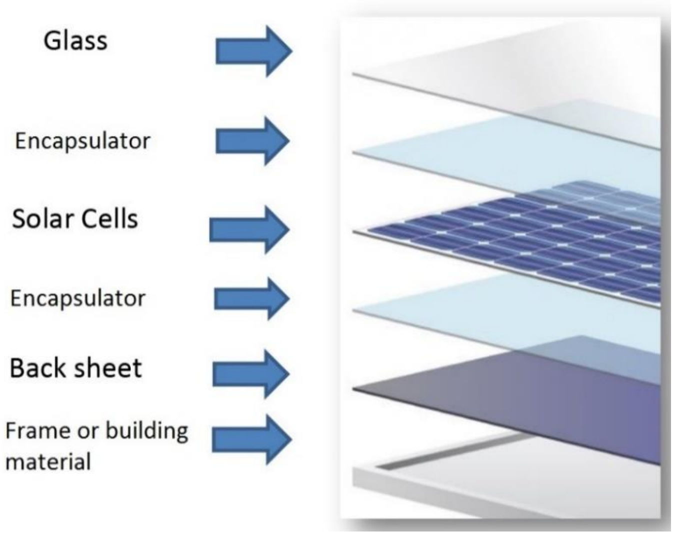


Fig 1.8 Typical PV module structure

In order to connect all components of the PV module together lamination is applied. This process is carried out in the laminator. When the module is assembled it is put into the machine. The laminator consists of two individual chambers, heating plate and membrane. It is important to avoid trapping of air or other gases inside the module, because it may lead to fast module degradation. Therefore, before the beginning of the process each chamber is evacuated to maintain vacuum. After that module is heated to melting point of encapsulating material and upper chamber starts to fill with air and press on the module through the membrane. When temperature reach 150 Celsius degrees, curing process begin. The whole process with commonly used materials for module preparation usually takes around twenty minutes. However, in our case preparation was about one hour.

In production process, lamination was always limiting step. As a result, new methods to reduce, lamination time were introduced. Laminators become bigger able to accommodate several modules at a time. In addition, improvements in encapsulating material enabled fast curing, dramatically reducing lamination time.

After module is cooled down and released from the laminator it is required to remove spread-out encapsulant material. Then, depending on the encapsulant material sealing with silicon to avoid thermal expansion may be applied. After that junction box is attached to the rear side of the module. Frame may be installed if required. The next step is to perform high voltage test to ensure electrical insulation of the module. In addition, I-V curve of module should be measured under standard conditions. Special flash simulators with electronic equipment are used for this purpose.

1.6 Adhesives

Adhesive is a complex substance capable of creating a strong joint between two or more parts of same or different materials on a permanent basis. There are other methods of joining such as fastening, sewing, welding, brazing, thermal bonding etc… However, adhesive bonding has several advantages compare to them. It distributes stress more efficiently over a bonding surface, cost effective for simple joints, easily applicable in most cases and provides aesthetic design. In addition, bonded structures usually have the same strength or even stronger than other joining methods. Among disadvantages are weak stability at high temperatures and difficulties in bonding large objects with small contact area. In general, adhesion occurs due to molecular interactions between substrate and adhesive. There are also cases when adhesion provided by chemical bonds. It is important to distinguish between adhesion and cohesion [16]. The last corresponds to intermolecular forces or forces which acts between molecules of one substance. Examples of adhesive and cohesive failures are shown on Fig. 1.9.

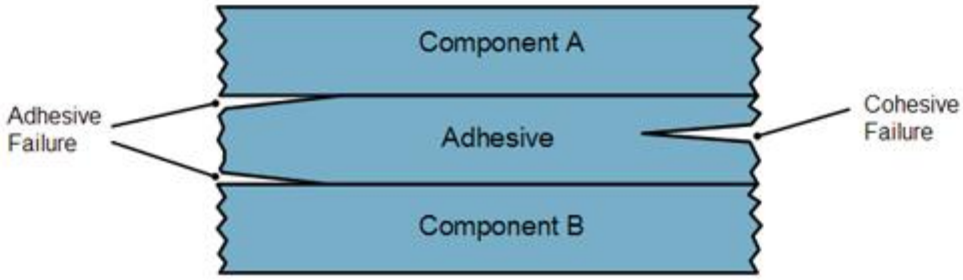


Figure 1.9 Adhesive and cohesive failures

1.6.1 Theories of adhesive bonding

There are several theories that explain adhesive bonding, which aroused separately, however none of them applicable solely to any specific bonding case. It is always convenient to rely on several theories to understand adhesive bonding. In addition, some theories may be more applicable for certain substances, where others applicable under certain circumstances.

Adsorption theory claims that adhesion occurs from molecular contact and forces that arise between adhesive and material. A bond results from adsorption of adhesive onto substrate and usually explained by van der Waals forces. Thus, for these forces to be created a proper molecular contact should be established, not more than 5 angstroms [16]. To provide such contact adhesive should fully cover substrate’s surface and penetrate into all cavities. This property of liquid is called “wetting” Fig. 1.10.

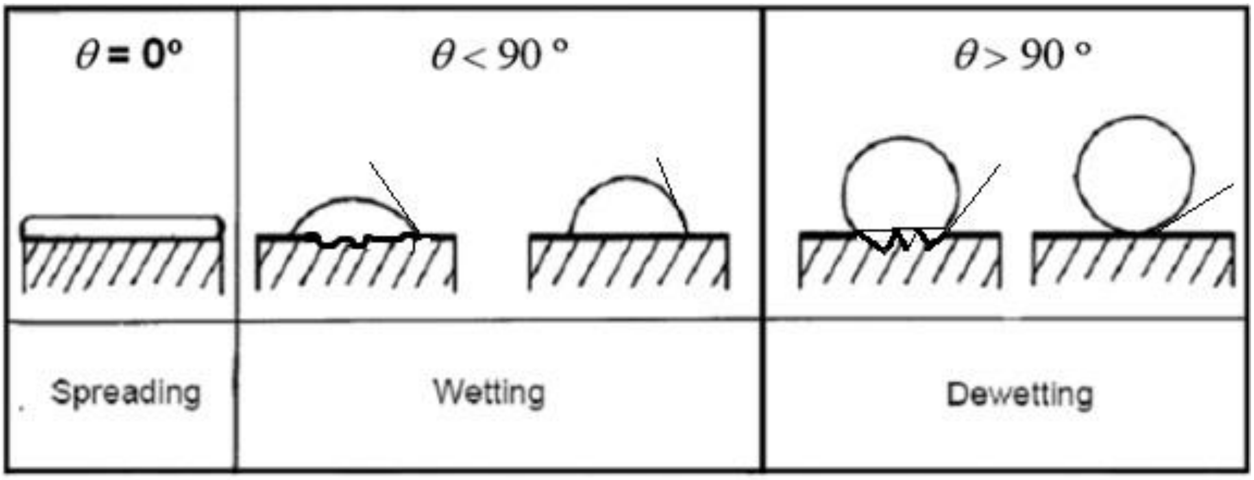


Fig. 1.10 Demonstration of good and poor wetting of substrate by adhesive.

Poor wetting provides less contact area between adhesive and substrate, thus stress distribution becomes unequal along joining area. Moreover, when bonding rough surfaces, air may trap on the interface layer that can change behavior of bond during exploitation in various environments.

Wetting is determined by measuring contact angle and described by Young equation:

$$\gamma_L \times \cos\theta = \gamma_S - \gamma_{SL}, \qquad (1.6)$$

where γ_L is liquid surface tension, γ_S is solid surface tension and γ_{SL} is tension on the boundary between liquid and solid. Good wetting occurs when surface tension is lower than substrate tension and vice versa. Therefore, it hard to obtain good wetting when bonding with low surface energy polymer structures. To provide better adhesion in case of these structure it is necessary either to reduce surface tension of adhesive or increase surface tension of substrate. In first case reduction of surface energy is achieved by adding to the adhesive wetting agent. Alternatively, surface treatment is applied to increase surface tension of substrates. Generally, there are three types of treatment: chemical, mechanical and energetic.

Mechanical theory states that surface is never perfectly flat and consist of pores, cavities, microvoids etc… Therefore, adhesive fills these unevennesses in substrate and, when cured, joint hold together mechanically. Adhesive agent should penetrate cavities, dislodge trapped air and create mechanical interlocking Fig. 1.11. Moreover, surface irregularities increase contact area, thus increasing total surface energy, which favors adhesion.

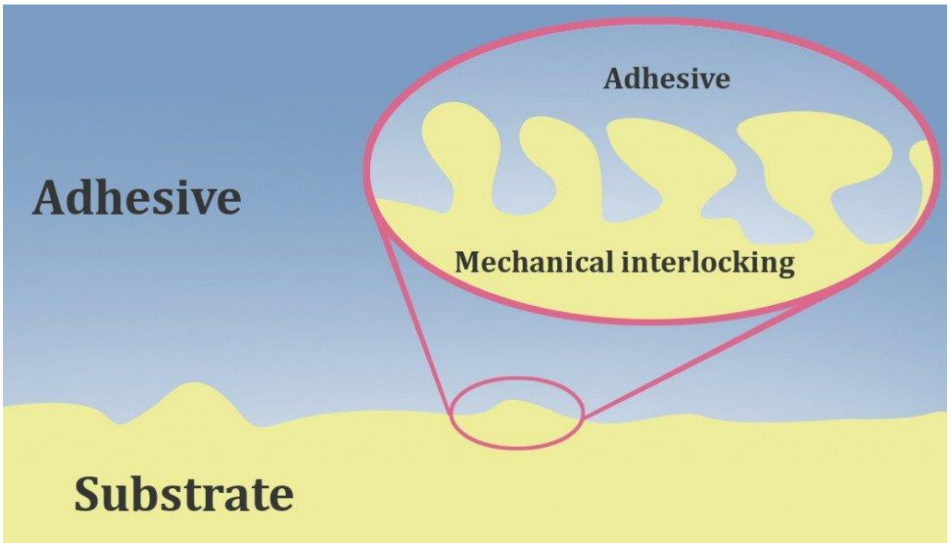


Fig 1.11 Mechanical interlocking

Surface roughness improves adhesion in several ways. Firstly, it causes plastic deformations in adhesive that absorbs energy, thus increasing strength. Secondly, it works as a barrier against crack propagation. Due to peaks on the surface force applied to the edge of the interface layer is dissipated and strength of a joint is increased [16]. Mechanical interlocking is considered in joints with porous substrates. Such materials as wood and leather can be easily penetrated by adhesives with smaller molecules. Different surface treatments provide roughness to metals improving adhesion.

According to **Electrostatic theory** forces in the form of electrical double layer are produced between adhesive and adherent [17]. Thus, forming bonding interface. These forces occur due to interaction of permanent dipoles and operate only on short distances. When distance is increased, their effect is reduced drastically.

The diffusion theory affirms that adhesion between adhesive and adherent arises due to molecular interdiffusion. It usually occurs when between polymers of long chain molecular structure. It is a two-step process, where wetting is followed by interdiffusion. Parts of adhesive chain penetrate into substrate and creates a network of molecules. This theory is applicable, when polymers are soluble into each other, have long molecular chains and diffusive molecules are mobile. Typically, it is applicable for thermoplastic substrates. There is no stress concentration near the interface, since no discontinuity exists between physical properties [17].

Mechanism of chemical bonding theory favors to the formation of chemical bonds on the interface layer. Ionic, hydrogen, covalent bonds may be formed, which are usually stronger than van der Waals forces or acid-base interactions. For chemical bonding to occur materials should consist of mutually reactive chemical groups. Generally, strong bonds occur as a result of adsorption of adhesive on the substrate followed by chemical reaction.

1.6.2 Classification of adhesives

There are a lot of materials that can be considered as adhesive. However, nowadays products mostly represented by polymeric materials. Polymer is a large molecule that consist of small repeated units called monomers. Size of the molecule is defined by the number of monomer repeated units. Usually, polymers represented by covalent compounds of carbon. Other elements that can be found in polymer chain are chlorine, oxygen, nitrogen, hydrogen and silicon. In general, polymeric adhesives are divided by chemical composition of three large groups, namely thermosetting, thermoplastic and elastomeric.

Thermosetting polymers cannot be reverted to initial state after curing. After reaching peak temperature in hardened state they experience decomposition. They consist of continuous network of polymer chains that are cross-linked Figure 1.12. Connecting chains of these polymers are held by covalent bonds, making it hard to move one chain relative to another. Thermoset adhesives cured by chemical reaction in room temperature or at elevated temperatures, depending on adhesive. In addition, some adhesives require contact pressure. They supplied as liquids, pastes or solids. These glues are represented as one- or two-part systems. One part systems are usually cured at elevated temperatures and have short shelf life, alternatively two-part systems can be cured at room temperatures and have long term shelf life [19]. Since these adhesives are densely cross-linked, they have good resistance to load, solvents and temperature. Bonds are able to withstand temperatures of 93 – 260 °C and peel strength is fair [19].

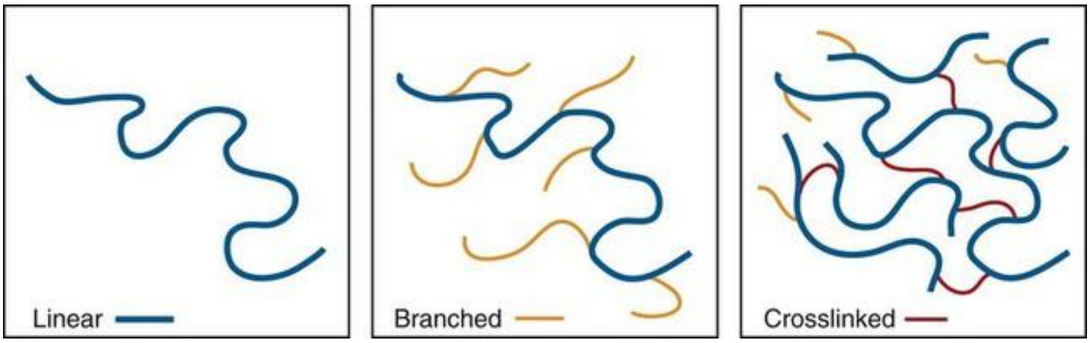


Fig. 1.12 Chain structure of linear branched and crossed-linked polymers

Thermoplastic adhesives melt under high temperatures and cured when cooled down. They may be decomposed only at extremely high temperatures. Thermoplastics have long chain linear or branched molecules that are not cross-linked as shown on Figure 2.3. Secondary intermolecular forces hold them together. Thus, when elevated temperature is applied to polymer, these forces become weak and chains are free to slide past one another. They have low resistance to heat, solvents and stresses. However, they are more flexible and have better resistance to peel and impact loads [19].

Elastomeric adhesives have better toughness and elongation. They are based on natural and synthetic polymers. These materials supplied in different forms such as organic solvents, dispersions, sensitive tapes, one- or two-part liquids or pastes. Temperature range from 60 to 205 °C is normal operating environment. They have great flexibility; however, their bond strength is relatively low as well as resistance to stress. Therefore, they are not considered structural adhesives and usually applied in low weight applications [18].

Structural adhesives are those intended to create bonds that are of the same strength or higher than bonded material. Their target to remove failure are away from joint. They have good resistance to moisture, temperature and different stresses. In general, they are used to withstand required load in certain environmental conditions for life expectancy of the joint. Alternatively, non-structural adhesives used to withstand low loads and mainly keep two parts of the joint together.

1.6.3 Adhesive properties

Molecular structure is an important parameter for adhesives, since it affects viscosity, elasticity and temperature stability. Linear and branched polymers are relatively easy to move with application of stress due to absence of interconnection between chains. In contrast, cross-linked polymers cannot be moved unless their bonds are broken. Rigidity, tensile, chemical and temperature stresses has proportional dependence with the degree of cross-linking for thermoset polymers.

Molecular chains in polymers can be aligned that they are crystalline, amorphous or combination of two Figure 2.4. Since crystalline polymers have densely packed chains and their intermolecular forces stronger than amorphous alignment, they have higher strength. Greater crystallinity results in higher cohesive strength. However, at some point increase in crystallinity creates excessively rigid polymers [16].

Polymer molecules experience permanent vibration, which depends on temperature. When polymer has crystalline structure, it means that it is more densely packed, has stronger bonds and less free volume to enable molecular movement. At elevated temperatures without significant stress molecules can move one relative to another, thus providing more free volume and faster molecular movement.

Free space also explains relationships with external solvents. Last penetrate into this free volume and replace interchain molecular bonds. Thus, linear and branched polymers are dissolved. Alternatively, cross-linked polymers have dense structure and are non-dissolvable [20].

Glass transition temperature is another important factor that explains behavior of polymers. At some temperature point molecular movement in polymer suddenly increases. This high temperature enables such vibration that molecular chains are broken apart and they can slip one another. Glass transition temperature shows the point at which reversible transition from glassy to rubbery state occurs. As temperature rises above glass transition point flexibility, deformation and solvent penetration significantly increase. In contrast, tensile strength and elasticity modulus decrease [20]. Polymers with T_g above room temperature exist as hard solid materials and show brittle properties, while polymers with T_g lower room temperature are soft and flexible.

1.6.4 Adhesive thickness

It is profoundly alluring to have a consistently thin (0.05-0.25 mm) cement bond line. Starved cement joints (where a few regions have no glue) result in poor bonds. Three fundamental strategies are utilized to control glue (security line) thickness. One of the method is to utilize mechanical shims or stops, which can be expelled after the curing activity. Here and there it is conceivable to configuration stops into the joints. In addition, work of a film glue that turns out to be exceedingly gooey amid the cure cycle, anticipating unreasonable cement stream out. With upheld films, the glue transporter itself can go about as the "shim." Generally, the cured bond line thickness will be dictated by the first thickness of the glue film. Moreover, utilization of experimentation to decide the right weight glue thickness factors that will yield the coveted security thickness [16].

1.6.4 Adhesive curing

Various high-strength basic glues must be cured to create joint quality. These materials exist in film and fluid form, the last normally depending on catalytic reaction to impact a cure. Use of a premixed fluid adhesive catalyst framework must be finished inside its working life if spreading, also wetting are to be satisfactory. Following its application, sufficient time must be considered the glue to cure. Room-temperature-curing cements frequently require a number of hours to set, albeit some that set during several minutes are also available. Some metallic adherends require an idle environment. A few glues contain volatile segments to enhance their consistency. In these cases, handling may include fluid evacuation (heat assisted) before curing happens. Different structures are provided as films, which might possibly be provided on carrier cloth. Structural adhesives films for the most part require maintaining high holding weights amid hot cure.

The correct conditions required for curing the adhesive joints rely upon the properties of the particular adhesives utilized. Producers generally suggest the ideal methodology. In many occasions, curing is performed through the utilization of heat, pressure, or both. Contingent upon the properties of the glue, cure pressure may extend from contact, 6.9 - 34.5 kPa, to 3447 kPa, while curing temperatures may extend from room temperature up to 350 °C. The regular most extreme temperature is often not more than 180 °C. Ceramic based cements rely upon a sintering activity for attachment amid which the temperature can achieve 1800 °C [22].

In single component adhesives, glue segments are premixed in their last extents. However, they are chemically blocked. Unless they are not subjected to the particular conditions which initiate the hardener they won't bond. In order to cure they require high temperatures or specific environment such as light or humidity.

Anaerobic glues cure under the absence of oxygen. Oxygen hinders the response in this manner averting cure. At the point when the cement is set in a bond line and the openness of oxygen is limited, cure continues quickly. Thus, the glue does not cure rashly, the adhesive in its holder must stay in contact with oxygen up until the point that it is utilized. This is accomplished utilizing air-penetrable plastic jugs which are just half filled and which, preceding filling, are flushed with oxygen. Anaerobic cements are thermosets and the subsequent bonds have high strength and high protection from heat. These joints are, nonetheless, exceptionally brittle and are not appropriate for flexible substrates. Curing happens only in the joined zone and only small gaps can be connected.

Cyanoacrylates are known for their "moment" connection to almost any surface. They are thermoplastic when cured and thus are constrained in temperature range and chemical permeability. These adhesives are prominent for holding a wide range of glass, most plastics, and metal.

Single part heat curing adhesives require high temperatures for a predefined timeframe to accomplish cure. Since they are heat cured, they provide high strength, heat and chemical resistance. These glues are supplied as liquid, glue, and film [23].

Single component moisture curing adhesives are developed with resins that respond to environmental wetness to create a cured polymer. In addition, they do not require heat or similar source of energy. Nevertheless, few days of ambient exposure may require to achieve full strength of the joint. When there is chance that there is excessive moisture present in the environment, curing of polyurethanes happens so rapidly that carbon dioxide become entangled in the adhesive layer creating voids. In contrast, at low temperatures, when there is lack of moisture curing process slows down and require more time [23].

Radiation curing cements do not require high temperatures, solvents or complex equipment to be cured. It cures under light waves of characterized wavelength. Curing times extend from as low as 1 second up to a few minutes. Commonly, radiation curing glues just cure amid the time they are open to radiation. Accordingly, they should be lighted after the substrates are joined. This requires at least one of the substrates to be transparent to the particular wavelengths of light that start the cure of the glue.

Two part glues are solid structures that may be stored by separating parts. They are provided as "rubber" and "hardener" in partitioned cans. It is imperative to keep up the endorsed proportion of the resin and hardener so as to get the coveted cure and physical properties of the glue. The two parts are combined to create the glue just before application with cure happening at room temperature. Since the curing ordinarily starts right after blending the two parts, the viscosity of the blended cement increases with time until the point when the cement cannot be used with the substrate or bond strength is diminished because of decreased wetting of the substrate. There are compositions with an assortment of cure speeds giving different working parameters (cure time) after blending and rates of strengths develop after curing. Maximum strength is built-up from minutes to weeks and depends on the composition. Glue must be cleaned from blending and application gear before cure has advanced to the point where the cement is insoluble. Contingent upon cure time, two segment cements can be connected by trowel, globule or lace, splash, or roller. Joints are normally fixed until required strength is reached. Heat can be used to reduce curing time if required. This is especially valuable when parts have post treatment after bonding or require additional cure time with fast curing. In the cured state, two segment cements have extreme strength and rigidity with great temperature and chemical resistance [25].

The most common structural adhesives are two part systems based on epoxy. They can be composed into fast curing mixtures with two to fifteen minutes cure time and usually are rigid and brittle. Compositions with longer cure time typically contain added substances to give flexible bond lines. Two segment epoxy cements are utilized to bond metal, plastic, fiber fortified plastic (FRP), glass, and a few rubbers.

MMA cements can give speedier quality develop than epoxy cements and are more tolerant of oil on the substrate. MMA glues are utilized for holding plastics to each other and for holding metals to plastics.

Two-part urethane glues can be defined with an extensive variety of cured properties going from delicate and adaptable to tough and flexible or hard and rigid. They are utilized to bond materials with various adaptability or distinctive warm coefficients of development including glass to metal, fiber strengthened plastic (FRP) to metal, and aluminum to steel.

1.7 Surface preparation

Since polymers have significantly lower surface energy comparing to other substances such as metals they tend to form weak bonding. Thus, surface treatment may be required to improve bond strength. Treatment impacts only connection zone of plastic material and does not change its bulk properties.

1.7.1 Effect of surface treatment

Currently, there are several surface preparation techniques available such as chemical, physical, and bulk material treatments. Chemical modifications incorporate those requiring moisture or chemical reactions as the essential methods for changing the surface, for example, wet carving, grafting, acid initiated oxidation, and plasma polymerization. Physical surface preparation strategies incorporate corona treatment, ion treatment, photon discharge (laser, bright light, and X-beam), plasma and fire treatments.

The modifications that arise in the surface of plastics by applying the treatment techniques are the aftereffect of the four procedures of cleaning, removal, cross-connecting, and surface chemical modification (mostly oxidation) [17]. All of the methods used are intended to improve surface energy of plastics. The polar segment of surface energy ought to be expanded by 15-20 dynes/cm to reach appropriate adhesive bolding in polymers such as polyolefin, polyphenylenesulfide, polyaramide, and others [26]. Moreover, additional changes in the material include increase in surface roughness, removal of weak boundary layer and strengthening the surface.

Changes in surface energy of plastics arise due to surface oxidation of polymer chains. For halogenated polymers, for example, chlorinated and fluorinated polymers, surface alteration includes huge dehalogenation, which is the exclusion of chlorine and fluorine atoms from the surface. Generally, surface treatment can be described as transferring of energy from the source of treatment to the surface. Moreover, surface treatment allows to remove different contaminations such as process oil, waxes and dirt. Clean surfaces must be glued quickly or covered with protecting material, since reaction with atmospheric environment is very fast and layer of contamination can cover the surface again. Plastic surfaces frequently contain a low sub-atomic weight polymer, for example, an oligomer or approximately reinforced issue, likewise called a weak boundary layer. The treatment techniques expel redundant material from the surface.

1.7.2 Surface cleaning

Plastic materials should be properly cleaned, with a watery cleanser arrangement washed with clean water and dried. The cleanser can be substituted by a solvent. Either solvent or cleanser can expel contaminative agents from the plastic surface. Generally, cleaners include such substances as methanol, acetone etc. and depends on the type of plastic. In order to properly select solvent resistance of the plastic material should be considered. Otherwise, inappropriate selection of cleaner may damage the plastic material itself. If advanced treatment procedure is used, such as plasma treatment, cleaning can be skipped, since it can also provide adequate cleaning of the surface.

1.7.3 Surface treatment

Abrasive treatment roughens the surface of plastic material and increases contact surface area. Weak and unstable polymers expelled from the surface. Generally, sand-blasting or hand-sanding is applied to increase surface roughness. However, it may become problem when considering aesthetics of the final product. In addition, polymer may have a thin layer such as in case when it covers metal sheet. Thus, it is possible to reach metal sheet during the procedure, which may negatively affect the device in future, for instance start corrode. From the other part, where back sheet, it is also possible to damage the structure and alter functionality of the material.

Corona discharge used at atmospheric pressure. It is a flow of electrons and ions, which are accelerated by electric field. It is created by application of high voltage to a volume with air or other gases to cause chain reaction of particles collision followed by generation of ions. It is applied to polymer surfaces to increase their adhesion. Impact of corona treatment on attachment of polyethylene to itself (autohesion) has been examined as a function of lamination and temperature. Studies show that corona treatment dramatically affects the adhesion of polyethylene with increased bond strength compare to untreated one [17]. However, efficiency of this methods depends on the type of polymer. Some polymers such as polyetherimide do not experience changes after corona treatment. Time required to increase surface energy of the polymer depends on morphological structure of the material. Hence, the higher crystallinity of the material, the more time require to achieve desirable result.

Flame treatment is another process to increase adhesion in polymer materials such as polyolefins and polyethylenes. In this process polymer surface is processed with oxidize flame that is created by mixture of hydrocarbon gases saturated with oxygen. The effect depends on the processing speed and composition of the gas mixture. The flame contains different particles such as NO, OH, and atoms of oxygen, which expel hydrogen from the surface and substitute it with functional groups, e.g. –C═O and –OH. PVF and PP have a surface energy of 36,7 and 30,1 mN/m respectively, which is usually not enough to obtain good adhesion [28]. In order to obtain good adhesion, it is required to increase to 38-42 mN/m. Flame treatment is easily controlled method for surface preparation, which is one of the reason that it is widely used. It is also easy to apply and provides opportunity to process non flat surfaces. Gas fuel mixture is utilized for this method, where air has high pressure of 138-345 kPa and gas is about 1,7 kPa. In general, butane, propane or methane are widely used. In order to achieve efficient surface treatment flame should be oxidizing, having blue color. For industrial implementation flame control systems are required with pressure and mixture proportion control. In addition, flame position, intensity and flame stability should be considered designing the system. Over exposure to flame may lead to surface damage and altering of material properties [17]. In general, flame treatment is considered as a cheap effective treatment for variety of applications.

Plasma treatment oxidizes the surface of the polymer within the sight of oxygen. It consists of a set of charged particles that comprise of positive and negative ions. It can, hence, expel natural contaminants from its surface. Early investigations have closed cross-connecting of low atomic weight surface species as the instrument for disposal of a feeble limit layer. Plasma is very reactive and easily modifies surfaces of plastics [29]. It may be used to increase surface roughness and hardness also make them more appropriate for adhesion. Later research has ascribed the adequacy of plasma treatment to surface cleaning, removal of surface polymer chains, surface cross-connecting of polymer chains, and presentation of polar useful gathering that outcome in expanded surface vitality. Plasma treatment is very effective and is advised for use with complex geometric structures and where strong bonds are required [30]. However, usually plasma treatment requires vacuum systems and expensive gases to operate, which is the reason it is not always used in industries. There are also have been developed atmospheric plasma systems that can be utilized under atmospheric pressure. It is design in the way that gas flow completely surrounds small objects penetrating into cavities and channels. Nevertheless, it requires of installation of complex system, which can be expensive.

Surface exposure time is an important step to be considered, while preparing material for bonding. It is a time between surface treatment and bonding procedure. If this time is more than one hour it is required to use protective films or other methods to avoid surface contamination. In addition, surfaces should not be touched by bare hands or dirty gloves. Different peel stress tests show that increasing surface exposure time have a negative effect on joint strength.

1.8 Bonding materials

In this work adhesive bonding between two parts of the BIPV module will be examined. PV module itself without framing connects with by means of adhesive bonding to metal sheet coated with polymer material. Thus, it is necessary to describe properties of both backsheet and coating materials.

There are several materials available on the market for solar backsheets. Several points should be taken into account when choosing backsheet for BIPV module. In general, it should satisfy basic requirements such as electrical insulation and minimum fire resistance. It is also important that material does not change aesthetics of the module, which means it should have the same color of the coated metal sheet or be transparent. In addition, it should have similar chemical and moisture resistance to encapsulated materials and satisfy price requirements. Adhesive properties are not the most important part here, since backsheets mostly designed for regular photovoltaic modules. However, some companies developed their own treatment or modified composition of the material to improve adhesive properties. For this experiment PVF and PP materials have been chosen.

Metal sheet has standard coating procedure, which is in this case application of polyurethane paint that gives black color to it and protects from environmental impacts.

1.8.1 Polyvinyl Fluoride

PVF is well research material and is used in PV industry for a long time. It has semicrystalline structure and planar zigzag chain configuration [31]. Its chemical structure is shown on Fig. 1.13. It has a melting point from 160 °C to 220 °C depending on the chain structure and orientation. This material has been heavily tested in different conditions and with different test. Results show its excellent resistant to chemicals, solvents, and stains. Moreover, is not permeable to oils and greases. In addition, it has low Water vapor transmission rate of 9-57 $g/m^2 \cdot d$ [32]. This is an important factor to consider, especially in humid Estonian climate. Those characteristics are a merit of presence of fluorine atoms in the structure of the material. PVF has good weather ability, which is resistance to sunlight exposure with combination of other environmental factors and do not show visual degradation, such as yellowing, bubbling and delamination as well as significant reduction in mechanical properties over a period of about thirty years in different climates [33]. Thermal tests show that it has good performance in temperature range from -72 °C to 107 °C. Also, its electrical characteristics satisfies requirements of electrical insulation for PV modules, which why it is used in industry [34]. PVF itself has relatively low surface energy that does not favor adhesion. In order to satisfy adhesive requirements special grades of PVF were developed, such as “A” (one side adherable) and “B” (two side adhearable) with adhesive for bonding to wide variety of substrates. These surfaces have excellent compatibility with wide variety classes of adhesives such as acrylics, epoxies, polyesters and rubbers [34]. The only drawback is a price of a material, which is still comparatively high even after years of its research and implementation.

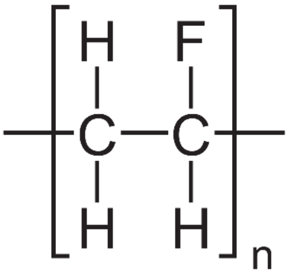


Fig. 1.13 Chemical structure of Polyvinyl fluoride

1.8.2 Polypropylene

PP was discovered in 1954 and has a long history of researches and development. Its molecular structure represents attachment of methyl groups to each second carbon atom in polymer backbone chains. Depending on the arrangement if methyl group distinguish three types of polypropylene Fig. 1.14. Isotactic product appears when all attached groups appear on one side of the chain. Syndiotactic PP is a serial alteration of methyl groups from both sides. Finally, atactic PP represents chaotic attachments of the groups to the backbone chain. However, only isotactic PP has properties required for useful plastic material. It is referred to semicrystalline polymer and its crystallinity depends on its expose to thermal stress during production. High crystallinity increases its strength, hardness, shrinkage, wear resistance and barrier properties. PP is a thermoplastic polymer with T_g about 0 °C. It becomes brittle and hard at temperature below -20 °C and softens above 20 °C. Practically, it withstands temperatures up to 150 °C after which melting is occur. Moreover, it has recrystallization temperature about 115 °C degrees and loses its shear modulus dramatically with further increase of temperature. It can be used continuously under maximum temperature of 100 °C, which is comparatively high then other polymers. PP has one of the lowest

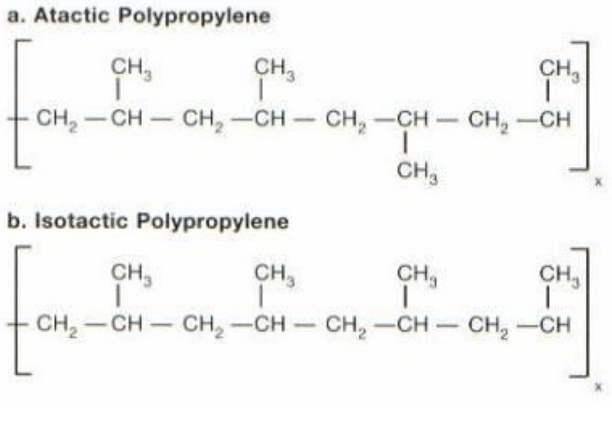


Fig. 1.14 Isotactic and atactic arrangements of polypropylene

surface energies 30,1 mN/m among polymers and require additional preparation of chemical modification to improve its adhesive properties [28]. Its dielectric constant is very low and mostly is not affected by environmental conditions such as temperature humidity etc..., thus making PP excellent electrical insulator. If not stabilized polypropylene has fast degradation under sunlight. Due to its high molecular weight and non-polarity it has great chemical resistance [35]. It is not affected by inorganic solutions of aquatic salts, which may be present in air if installation place is close to sea. PP is almost impermeable to moisture based solutions, its water vapor permeability is only 1 $g \cdot m^{-2} \cdot d^{-1}$, which is one of the lowest among polymers. In addition, it has no toxic substance and very cheap compare to other polymers. If an issue with adhesion can be solved, this material can be considered as one of the best suitable candidates for PV module backsheet [36].

1.8.3 Polyurethane

Polyurethane based coating applied to metal sheets to improves their resistance to corrosion. In our case metal sheets covered black color polyurethane coating. They applied mainly if forms of dispersions and can be prepared from two or single component polyurethane. Both solvents have almost similar properties such as high mechanical resistance, chemical resistance, light resistance and weatherability. The difference is in the curing method and time, which divides polyurethane coating on areas of application.

1.9 Stress analysis

In order to be reliable and have a long life, BIPV module should satisfy basic stress requirements after adhesive bonding. Main tests which determine, whether the module configuration is lasting or not, are peel and shear stress tests.

1.9.1 Peel strength

Peel strength is determined as a load per unit width required to separate materials from each other when pulled at a certain angle. It is used to estimate how good specific adhesive is in bonding two materials together. Generally, angle of 180° is used, however there are variations when 90° and 45° are applicable. In our case tests are performed at 90° Fig. 1.15.

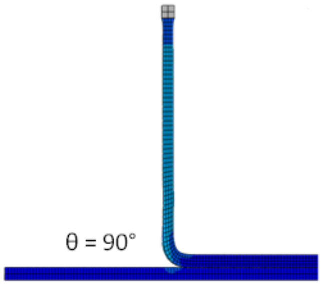


Fig. 1.15 Peel stress test under 90° angle

1.9.2 Share strength

Shear stress is applied parallel to the bond line and bonding surfaces Fig. 2.6. This test is easy to create and simulation is close to the conditions under which real device will work. Since BIPV modules installed on roofs, they always will be oriented under a certain angle. In such position BIPV module will experience a constant shear stress. It arises from the weight of photovoltaic module bonded with metal sheet, thus bond line will experience certain stress. Shear stress is calculated as load per bonding area. Usually, load applied to both surface connected by adhesive, however in this our case we have so called sandwich structure and constant load is experience by only one of the surface.

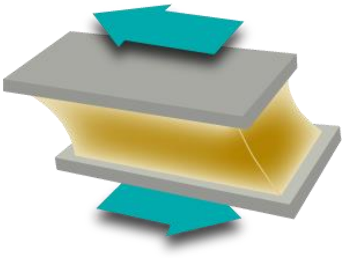


Fig. 1.16 Shear stress

2. Experiments description

In cleaning as well as in treatment there was a distribution of different surface cleaning and preparation. The idea is to see how different techniques affect adhesion of the samples and to find the easiest and cheapest method, which satisfies requirements. Cleaning and treatment has been applied only to metal sheet covered with polyurethane coating, since backsheet producers indicated that their products, PP and PVF, have special modifications that favors adhesion and can be used without any treatments. Therefore, in further text words sample/samples will refer to metal sheet covered with polyurethane coating. In addition, metal mash was applied as the middle structure in assembly between substrate and backsheet in order to avoid breaking of backsheet. Thus, the results may contain error, however they were used mainly to compare results with laminated product, which peel strength at failure was 300 $N \cdot cm^{-1}$. Backsheet material was used in the form of stripe as shown on Fig 2.1.

2.1 Experiments with PVF backsheet material

2.1.1 Surface preparation of samples

Three samples were cleaned with Loctite SF 7063 to remove greases, oils and other contamination. After that surface was left for 15 minutes to allow cleaner to fully evaporate from the surface. PVF surface was wiped with clean cloth to remove dust particles.

2.1.2 Application of adhesive

Three different glues were used to bond backsheet material to metal sheet. Two component polyurethane based Loctite 8103, that has liquid consistency, was mixed with ratio 1 to 5 and applied to cleaned sample. After that, backsheet material was put on the glue with little application of pressure. No continuous pressure was required. Then BIPV module was put in horizontal position for 48 hours to reach full curing strength. One component polyurethane based Loctite 7228 in the form of viscous liquid was applied to clean substrate. Continues pressure was applied for 15 minutes to enable proper curing. Then BIPV module was put in horizontal position for 48 hours to reach full curing strength. Contact pressure sensitive adhesive Teroson VR 5000 was applied from aerosol can as a spray to both sample and backsheet surfaces. It was then left for 10 minutes to make adhesive dry and slightly tacky. After that bonded parts were bonded together with application of pressure for short time. This glue reaches its full strength approximately in an hour.

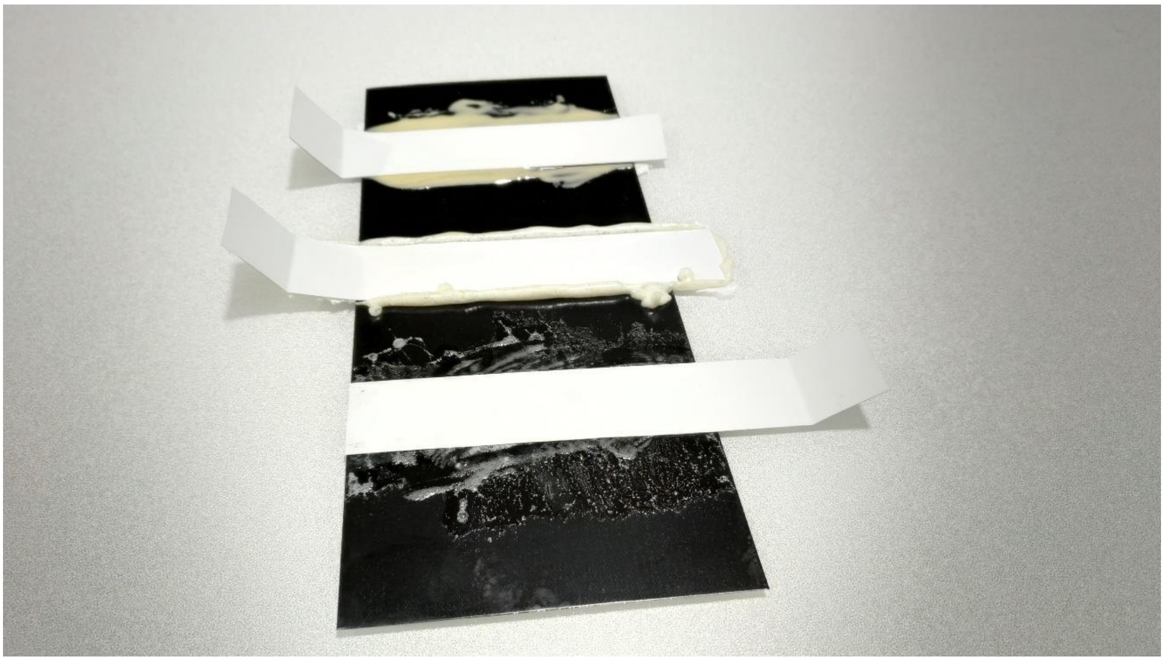


Fig 2.1 Samples with PVF backsheet material

2.2 Experiments with PP backsheet material

2.2.1 Surface preparation

There were three type of treatments for sample surfaces prepared for this experiment: plasma treated, alcohol cleaned and without treatment. Surfaces were exposed to plasma treatment for several second and then adhesive was applied in 10 minutes. Surfaces treated with alcohol, were wiped with isopropanol and left until full evaporation of alcohol. Additional test has been performed for PP with two component polyurethane adhesive mentioned in previous section, in which same treatment was applied.

2.2.2 Application of adhesive

Six different adhesives were used for this experiment and butyl tape. Teroson VR 5000 was applied in the same manner as was previously described to 3 types of treated surfaces. Backsheet material was then pressed to the surface with significant pressure over short time. Rubber based Teroson SB 2444 was applied with brush to 3 treated surfaces. It was then left open for time from

5 to 15 minutes, which was determined by finger test (the adhesive should be dry and tacky). The other parts were then pressed to surfaces quickly. Samples were left for 48 hours for full cure. Teroson SB 914 was applied in the same way as previous adhesive. Teroson 939 known as MS polymer was applied to treated surface with as a thin layer. Next, backsheet material was pressed to the adhesive and left until full cure. Two component polyurethane based adhesive was applied in the same way as mentioned in precious section without any additional treatments indicated in this part. Two component acrylic adhesive Permabond TA4610 was applied to treated surfaces. Low pressure was applied for several minutes to achieve handling strength. After that module was left for 48 hours to reach full strength. Butyl double side adhesive tape that was obtained from Loctite was bonded to treated surfaces. Then backsheet material was bonded to another side of the tape. Sample has been left for few hours to fully cure.

2.3 Testing

All samples were tested for peel stress test. One end of the stripe was clamped by grips, which were connected to hand electronic scales. After that pulling force has been applied under 90° to the surface until failure is observed. The number at which failure occurred was recorded and final value was calculated by the equation:

$$\varphi = \frac{m \times g}{l}, \tag{1.7}$$

where φ is peel strength at failure in N·cm, m is load applied in kg, g is gravitational acceleration approximated to 10 $\mathrm{m \cdot s^{-2}}$ and l is the bond line width in cm.

Three samples with adhesive MS polymer, Permabond TA4610 and two component polyurethane were additionally tested for shear stress. Connection method for samples is the same as was described for peel stress. Pulling force was applied parallel to the sample. Shear strength at failure was determined by equation:

$$\sigma = \frac{m \times g}{A}, \tag{1.8}$$

where σ is shear strength in $\mathrm{N \cdot cm^{-2}}$, m is mass in kg, g is gravitational acceleration in $\mathrm{m \cdot s^{-2}}$ and A is area of the bonded part in $\mathrm{cm^2}$.

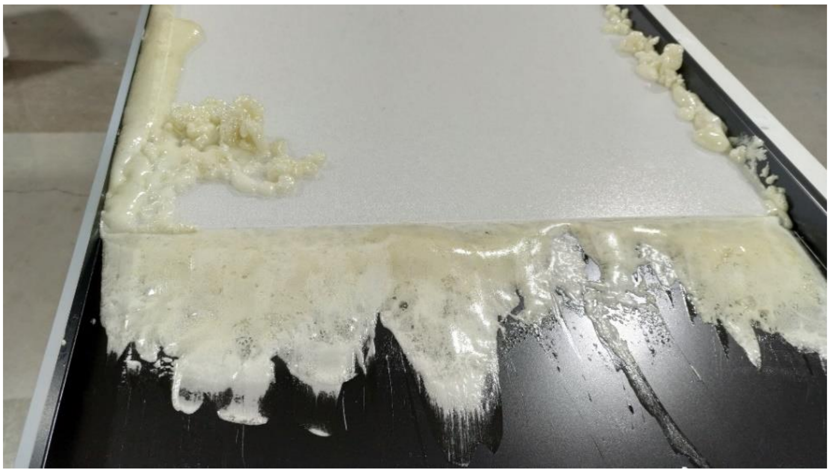
3. Results and discussion

3.1 Adhesive bonding with PVF

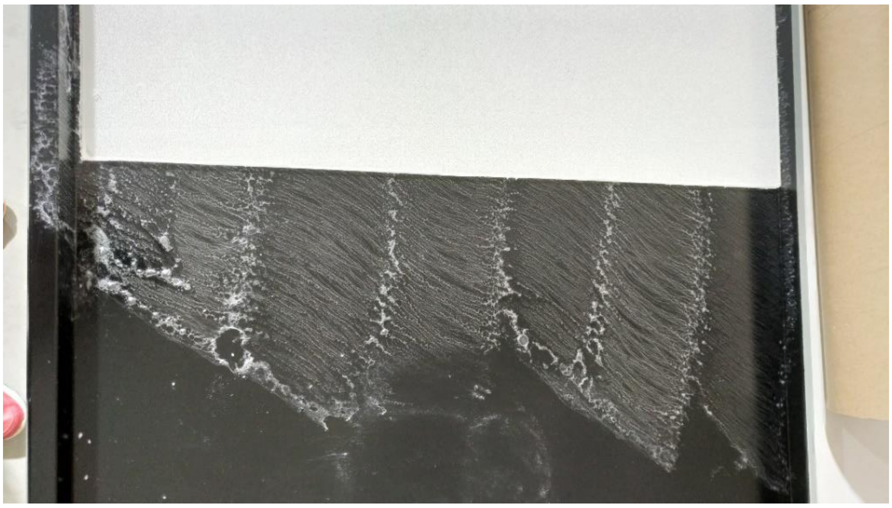
3.1.1 Visual appearance of the module

Adhesive was applied to whole module as shown on Figure 3.1. As can be seen from pictures one-part polyurethane glue forms excessive foaming when curing and gradually expands. One of the drawbacks is that continuous application of pressure required during curing process. The other is that the foam is very sticky and it is hard to remove it during curing phase especially when the load is applied and from the edges of contact with metal sheet part. Moreover, after curing it is almost impossible to remove residues without damages parts of the module. This significantly affect aesthetic view of the module and cannot be considered as a successful final product. One of the possibilities to avoid it is to cover parts aside of the glass and surface of the glass with tape that is not permeable to glue and remove it together with residues after curing. However, it makes production complicated by adding one more step to it. Second sample demonstrated on Fig. 3.1 (b) also shows traces of sprayed glue on the surface of metal sheet. The nature of spraying does not allow to apply glue precisely, which is the reason why residue is always left. It is also hard to remove them both before and after curing. However, in this case it is possible to cover area that is outside the required and remove tape after adhesive is applied. Since it is not liquid and does not expand, it is possible to cover only required are. Still the additional preparations required for application. Some initial pressure is required to achieve handling strength. The advantage is that it fully cures in an hour.

(a)



(b)



(c)

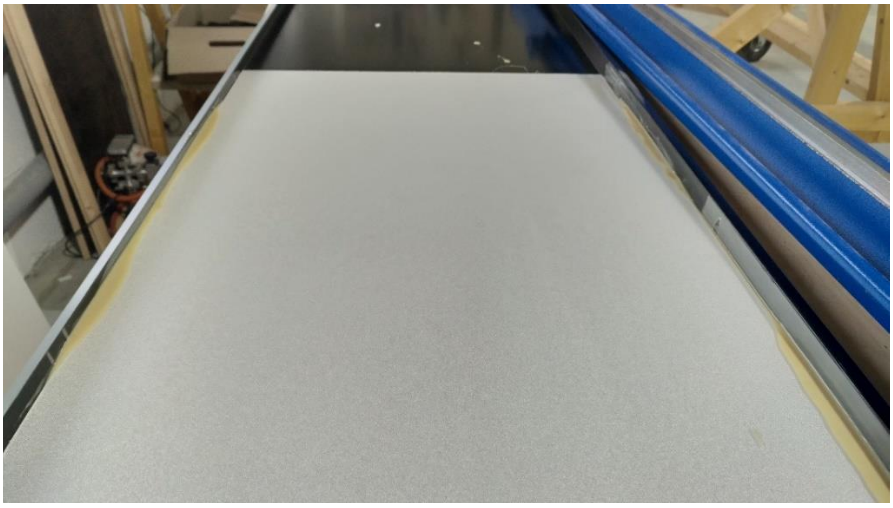


Fig 3.1 Cured adhesives in BIPV module samples (a) one-part polyurethane (b) Teroson VR5000 spray adhesive (c) two component polyurethane

Last picture on Fig. 3.1 demonstrates that two-part polyurethane glue does not have that much residues as previous adhesives. It is not expandable and relatively viscous which does not allow it to spread over the surface easily. There are few parts of the module where it is visible that residues left on sides pushed out by pressure. It is possible to remove them after PV module set up on the metal sheet. It is easy to do it with cleaners. However, when cured, it is though and hard to remove. Thus visual appearance of this glue is more appropriate than others, but still requires removal of residue from the surface of the glass.

3.1.2 Peel test results

Results after peel stress test are demonstrated on Fig. 3.2. Teroson VR5000 has shown 14 N/cm strength at failure. Adhesive failure from polyurethane side was observed. As can be seen from the picture, structure of the glue has air bubbles. This phenomenon may have negative impact on lifetime of the module. Moreover, recorded strength is lower than required for regular modules which is 20 N·cm. In addition, adhesive failure from the side of substrate means that glue does not perform its function in this particular case. One component polyurethane adhesive has shown strength at failure 20 N·cm. Adhesive failure from substrate side and cohesive failure of PVF backsheet were observed. Two component polyurethane has shown 22 N·cm strength at failure. Cohesive failure of PVF was observed. In this case glue performs their function by holding two parts together. However, in operating environment it may not be enough. Moreover, it is impossible to measure maximum strength of the adhesive, since one of the component breaks up at certain strength. As a result, two component polyurethane may be considered for further applications in assembly of BIPV module. However, it still requires several modifications in production line. Since other adhesive do not satisfy desirable requirements in adhesive strength only two-part polyurethane was chosen to continue testing and preform share stress test. In addition, PP was used to determine strength at failure, because PVF experience cohesive failure during tests.

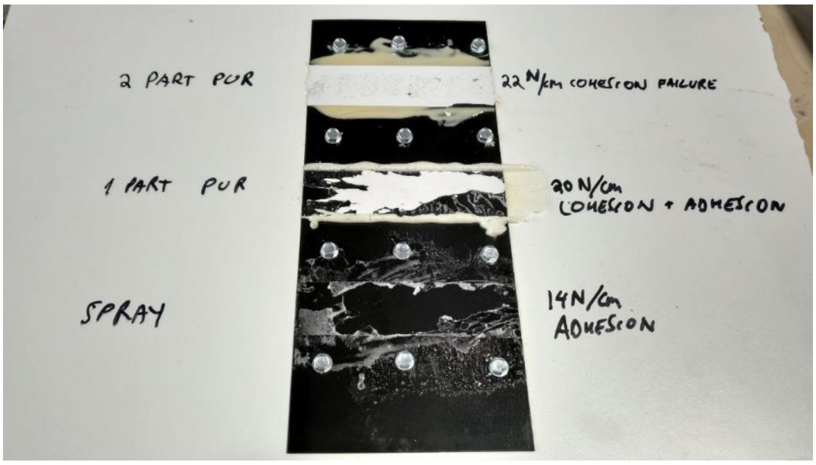


Fig. 3.2 Visual appearance of samples after peel stress test

3.2 Adhesive bonding with PP

Adhesives that will be described in this section were not applied to real size module to examine visual appearance due to the reason that they have the same or similar structure as previously tested adhesives e.g. liquid or the structure which final result is easy to imagine such as double side tap and paste. In several samples metallic grid was applied as a middle layer between PP stripe and metal sheet. The reason of this is that PP cannot withstand too high stress and breaks during the peel stress test. It has some effect on the test, however it is not significant.

3.2.1 Peel test results

Test with Teroson SB 2444 is shown on Fig. 3.3. As can be seen from the picture, there is a lot of trapped air in form of bubbles inside the glue. During the service cycle when exposed to environment, moisture can penetrate into those parts of the glue and destroy adhesive from inside. In addition, effects of temperature fluctuations may also cause destruction of the adhesive through air bubbles. Sample with plasma treatment has shown strength at failure 97 N·cm. Alcohol cleaning yield the result of 52 N·cm, whereas sample without treatment has shown 47 N·cm. All of the samples failed adhesively from substrate side. In general, plasma treated result of peel stress in relatively high, however cured state of adhesive is not acceptable for its application in the module.

Fig 3.3 Samples with SB 2444 adhesive before and after peel stress test. Surface treatment from left to right: plasma, alcohol, no treatment.

Plasma treated substrate for Teroson VR5000 has shown significant improvement in strength to 47 N·cm. Test result is shown on Fig. 3.4. Sample experienced adhesive failure from substrate side. Alcohol treated sample yield the result of 18 N·cm and demonstrated adhesive and cohesive failures. Cohesive failure may be explained by formation of weak boundary layer near the surface of substrate.

Fig 3.4 Peel stress results of Teroson VR 5000. Treatment from left to right: plasma, alcohol.

Teroson SB 914 has similar cured structure as SB 2444. Many bubbles of air trapped inside the glue can be seen on Fig 3.5. Plasma treated substrates has shown strength at failure of 54 N·cm with cohesive failure of the glue. Alcohol cleaning yields 30 N·cm with cohesive failure of the glue. Sample without treatment has strength of 25 N·cm and failed cohesively in adhesive layer. These results are relatively low and were rejected for further testing.

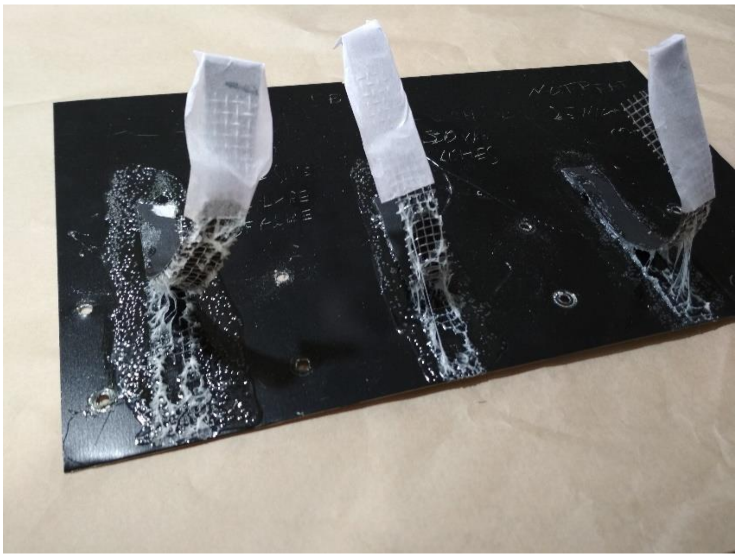


Fig. 3.5 Peel test samples with SB 914 adhesive. Surface treatment from left to right: plasma, alcohol, no treatment

Tests with butyl tape are demonstrated on the Fig. 3.6. Butyl tape yields strength at failure of 43 N·cm, 40 N·cm and 32 N·cm for plasma treated, alcohol cleaned and no treatment surfaces respectively. Samples showed adhesive failure from substrate sides. Butyl tape was considered as promising material to use for adhesive bonding due to its ease of application and immediate readiness for exploitation. However, test results were relatively low. Moreover, the material itself has soft flexible rubber structure and can be easily deformed. That is a great disadvantage when it is experiences constant load under the module, which may shift the module due to deformation of the tape. This material was not chosen for further test.

Fig. 3.6 Peel test results for butyl tape. Surface treatment from left to right: plasma, alcohol, no treatment

Teroson 939 known also as MS polymer, was design to bond different materials. Test results can be seen on Fig. 3.7. Recorded strength at failure with plasma treated sample was 121 N·cm and has shown cohesive failure of the glue. Alcohol cleaning yielded the result of 105 N·cm, also cohesive failure. Surface without treatment failed at 100 N·cm and adhesive failure from substrate side was observed. This adhesive is supplied in form of paste and cured with the help of moisture. Some residues left on the edges after application, which can be removed with napkins. When considering application, it should be noted that it is hard to cover whole area of PV module with this glue. First it is delivered in small cans and should be used with the pressure gun, thus to cover whole area several cans required. Second is that the price is to expansive to apply the glue for whole area. The most reasonable application is to cover edges of the PV module and bond it to metal sheet.

Test samples can be seen on Fig. 3.8. When applied it has some residues left aside. They are relatively sticky, but can be removed with cleaning agents. It has off white color and strong odor.

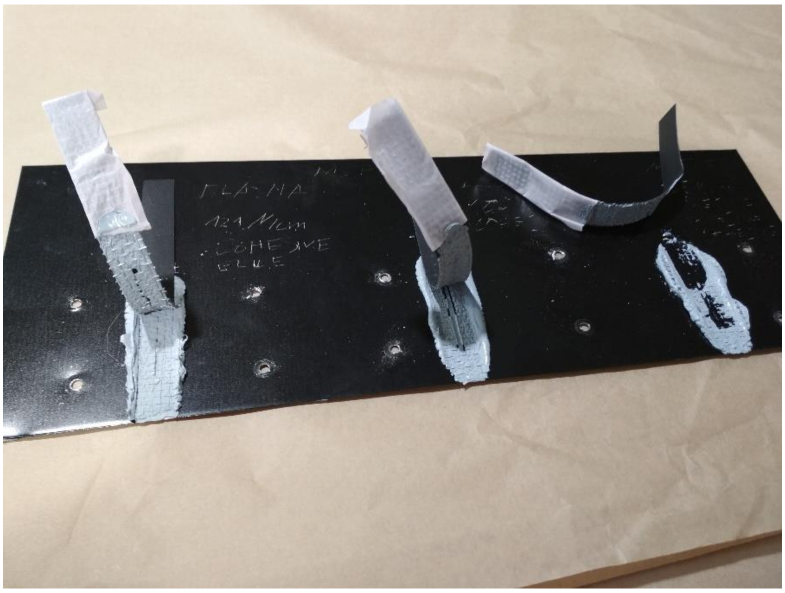


Fig 3.7 Peel test results for Teroson 939. Surface treatment from left to right: plasma, alcohol, no treatment

Test with plasma treated surface has shown strength at failure of 130 N·cm with cohesive failure of the glue. Alcohol cleaning yield the result of 125 N·cm with the same type of failure. Sample without surface treatment resulted in 115 N·cm with adhesive failure from the substrate side. It can be inferred that surface treatment does not have significant effect on results of experiments. However, in the last case non treated surface changes the type of the failure for the glue. Finally, this adhesive has shown best result of adhesive strength on peel test among other materials.

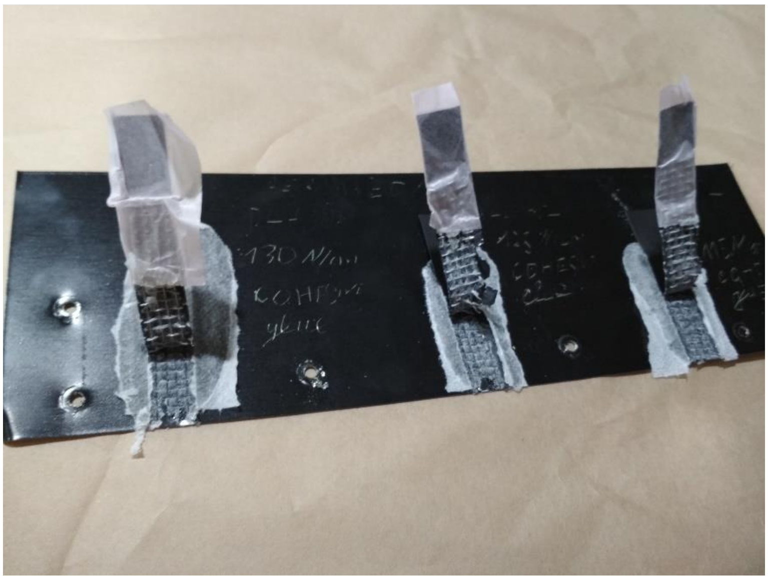


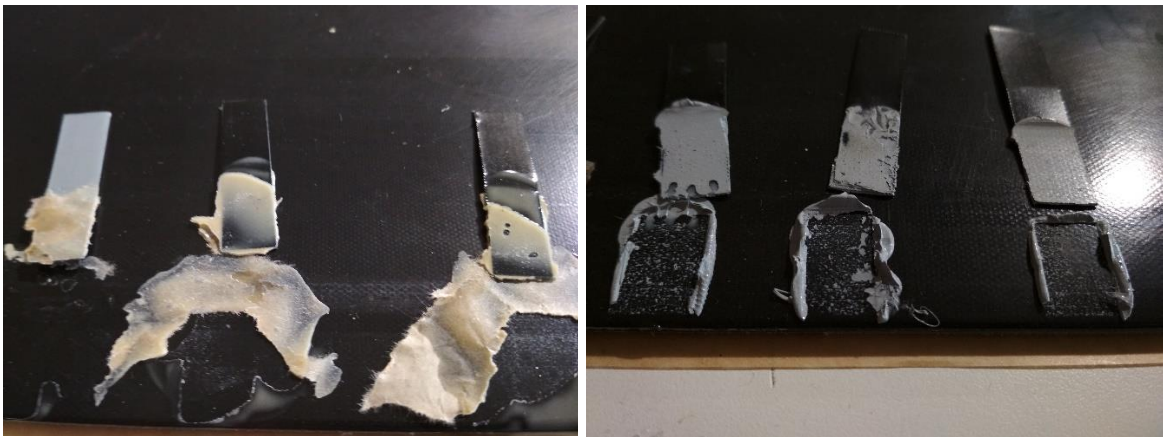
Fig 3.8 Surface treatment peel stress results Permabond TA4610. Surface treatment from left to right: plasma, alcohol, no treatment

Test for two component polyurethane has shown 105 N·cm^{-1} and failed adhesively from PP side.

3.2.2 Shear stress results

Three adhesives were tested for shear stress namely Permabond TA4610, Teroson 939, two component polyurethane. Glues were applied to PP surface, cleaned with alcohol, and small stripes of metal sheet covered with polyurethane were bonded to it. Then glues were left for 48 hours to cure fully.

Test results for two component polyurethane adhesive are depicted on Fig. 3.9 (a). Plasma treated sample has shown strength at failure of 296 N·cm^{-2} and adhesive failure from backsheet side. Alcohol treated sample has shown significantly lower result with of 160 N·cm^{-2}. Lastly, sample without treatment demonstrated the result of 100 N·cm^{-2}. It is clearly seen that bonding strength significantly rises from sample without treatment to plasma treated sample. However, it is not completely understandable what is the reason behind those change, since treatment was applied to metal stripes, but failures observed from PP side. One of the explanation could be that treatment also affect adhesive itself and modifies structure in the way that new bonds created even from another side of bond. When it might be true for plasma treatment, which oxidizes the surface, it is hard to explain additional effect of alcohol cleaning except expelling dirt from the surface.



(a) (b)

Fig. 3.9 Shear stress results for two component polyurethane (a) and Teroson 939 (b) adhesives. Surface treatment from left to right for both adhesives: plasma, alcohol, no treatment.

Teroson 939 results for shear stress were almost the same for each sample. Visual appearance after test is demonstrated on Fig. 3.9 (b). Plasma treated surface had the result of 130 N·cm^{-2}, alcohol treated is 120 N·cm^{-2} and sample without treatment yield 125 N·cm^{-2}. All of the samples failed adhesively from PP side as can be seen on picture. Presumably surface treatment does not have any significant result for this particular case and difference in results may be explained by measurement error.

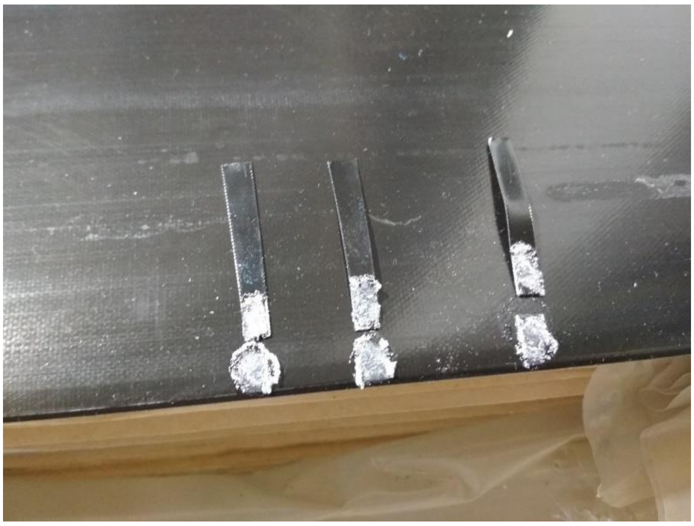


Fig. 3.10 Shear stress results with Permabond TA4610. Surface treatment from left to right: plasma, alcohol, no treatment

Test results of Permabond TA4610 are demonstrated on Fig. 3.10. Recorded result of shear stress for plasma treated sample is 280 N·cm^{-2}. Alcohol treated surface failed at 364 N·cm^{-2}. Test on surface with no treatment showed result of 360 N·cm^{-2}. All of samples experienced cohesive failure of the glue. The reason for unexpected low result for sample with plasma treatment is probably that it was damaged during connecting of the measuring equipment. Thus it is discarded from further analysis.

Short summary of pros and cons for the best adhesives are indicated in Table 3.1. As can be seen Permabond TA4610 has shown maximal values for both tests with plasma treatment for peel stress test and alcohol treatment for shear stress test. However, it should be taken into account that test results for shear test with plasma treatment were probably not correct, due to possible damage of sample. In addition, it can be seen that price of this adhesive significantly higher than others. Furthermore, the glue has a strong smell and it is hard to work with it continuously for a long time, but it is not a problem for automated production. Moreover, considering paste glues price in general, it can be concluded that their application for BIPV modules limited only to bonding along edges, since the price to cover whole area will make module approximately twice expensive. From the other hand it opens potentially new application to bond PV module directly to installed roof material and not to prepare BIPV from scratch.

Table 3.1 Test results and properties of adhesives. Best adhesives are bolded.

1. Adhesive	**2 part polyurethane**	**Permabond TA4610**	**Teroson 939**	Teroson SB914	Teroson SB2444	Teroson VR5000 spray	1 component polyurethane
2. Price EUR	9,92 hardener ratio 1; 2,9 adhesive ratio 5	14,8	8,8	N/A	N/A	11,2	6,1
3. Quantity	1 kg	50 ml	570	N/A	N/A	400 ml	1 kg
4. Best shear test result $N\cdot cm^{-2}$	296	364	130	N/A	N/A	N/A	N/A
5. Best peel test result $N\cdot cm^{-1}$	105	130	121	54	97	46	20
6. Best treatment for peel test	Alcohol	Plasma	Plasma	Plasma	Plasma	Plasma	Alcohol (no test with plasma)
7. Best treatment for shear test	Alcohol	Alcohol	Plasma	N/A	N/A	N/A	N/A
8. Other properties	Liquid, residues required to be removed; Curing time 48 hours	Strong smell, little residues, paste consistence; Curing time 48 hours	UV resistant, Paste consistence; Curing time 3mm per 24 hours	Rubber nature, many bubbles, liquid consistence	Rubber nature, many bubbles, liquid consistence	Foam consistence, some bubbles inside the glue, fast curing up to 1 hour	Foam structure, expands while curing, require constant pressure for 20 min to cure

Summary

In present work the idea to bond parts of PV module adhesively was considered. Metal sheet covered with PUR coating was used as a substrate. Two backsheet materials were used for testing namely PVF and PP. Several adhesives were chosen for experiments either for their known properties or by the recommendation of manufacturer, since companies apply many modifications to adhesives and give them new properties, which allow to bond to materials they were initially not able to bond. Samples were divided on three categories namely substrates with plasma treatment, alcohol cleaning and surfaces without treatment. Shear and peel stress tests were conducted to estimate reliability of the samples, their bonding strength and end visual appearance.

Two component PUR, Permabond TA4610 and Teroson 939 demonstrated best results for both tests. Permabond TA4610 had the highest result for both tests: shear test – 364 N·cm^{-2}, peel test – 130 N·cm^{-1}. Maximum result was shown with plasma treatment of substrate surface for peel stress test and alcohol cleaning for shear stress test. It is important to note that presumably sample with plasma treatment could also yield the best result for shear test, however, it is possible that it was damaged during the testing procedure, which is the reason alcohol cleaning has maximum output. It was found that substrates in most of the cases experience cohesive failure in adhesive layer, which means that the glue bonding strength to tested materials is high enough to bond them to the glue, but inner strength of the glue itself is limited to certain limit. In addition, in several cases were noted that samples with surface preparation that has failed cohesively in the glue layer had different test values. It may be possible that surface preparation also affects the inner structure of the glue itself, increasing its strength.

Two of the best adhesives have paste consistence, the other is liquid. It is required about 1 kg of adhesive two component polyurethane to bond whole module together, which has 0,8 cm^2 area. Paste adhesives reasonably to use only to bond edges of the module, since their price is to high to cover the whole area of module. However, that means that it could potentially be applied in to already covered roofs. That may create new opportunities in BIPV industry.

In conclusion, adhesive bonding may be potentially applied for small companies, who purchase parts of the modules separately, and does not require big investments in machinery. In addition, opportunities with bonding PV modules to already made roofs should be examined. Several other testing are required to proof reliability of the modules namely accelerated aging, fire resistance testing and others.

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