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Thermal Dissipating Composite Coated PosMAC Steel Sheets for Building Integrated Photovoltaic Module

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As an eco-friendly energy source, building-integrated photovoltaic (BIPV) modules that incorporate building materials and flexible solar cells are rapidly advancing. However, semiconductor-based solar cells often experience reduced power generation efficiency due to rising summer temperatures. To address this issue, thermal-dissipating composite-coated PosMAC steels with excellent thermal radiation properties have been developed as backsheet materials for BIPV modules. These steels are manufactured by applying a highly durable coating with both excellent thermal radiation and corrosion resistance characteristics on both sides. The front side, where the solar module is attached, is treated with a black-colored solution that includes high-crosslinking polyester resin and thermal conductive pigments to ensure corrosion resistance for over 20 years. The rear side is coated with a dispersive polyester polymer resin solution containing thermal conductive pigments with significant anisotropic properties, which greatly enhances heat dissipation by forming fine wrinkles on the surface to maximize surface area, achieved by adjusting the content of the hardening catalyst. This paper describes the thermal characteristics evaluation of the thermal-dissipating composite coated on PosMAC steels, as well as the fabrication of two types of BIPV roof modules combined with CIGS solar cells.

Keywords: *BIPV, Building integrated photovoltaic, PosMAC, Thermal dissipating steels, Thermal Emissivity*

1. Introduction

Recently, solar cells have been in the spotlight as eco-friendly energy that can overcome global environmental problems such as CO_2 emission and fine dust generation due to excessive use of fossil fuels. Solar cells are the most widely used technology for converting light energy into electrical energy by photoelectric effect. Recently, the manufacturing technology of Building Integrated Photovoltaic (BIPV) modules for application to roofs or walls of buildings using highly efficient thin film-type CIGS (Copper-Indium-Gallium- Selenium) solar cell has been greatly developed [1,2]. However, while solar module manufacturing technology has great advantages as an eco-friendly energy technology, it has three problems to overcome for mass application. First is a structural problem, with crystalline silicon solar modules using tempered glass as a front sheet material, the module's weight and safety against the environment (hail, typhoon) are insufficient. To compensate for these shortcomings, the cost of installation is high because modules are installed in additional steel structures. The second is the heat problem. Since solar cells produce electricity using the properties of semiconductors, not only depend heavily on the amount of sunlight, but also there is a problem that the power generation efficiency due to heat on the surface is greatly reduced as the temperature rises in summer. At approximately 45 ºC or above the surface temperature of the module, the power generation efficiency is rapidly reduced to -0.45 %/ºC. If the surface temperature of the module is maintained at about 60 to 90 ºC in summer period, when the temperature of the atmosphere is the highest, the average solar power generation efficiency will drop to 12 to 25% [3,4]. To address this, additional cooling systems such as coolant dispensing and heat dissipation fans are being attempted, but are not desirable in terms of cost-effectiveness. Third,

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it is a problem with the manufacturing process, and the production cost of solar modules is high because the process is not automated. In particular, the use of thick tempered glass hinders safety, weight and continuous production process.

In this paper, the development of thermal dissipating composite coated PosMAC plated steel sheet to improve thermal radiation properties of steel surface for use as backsheet of solar module and the fabrication of BIPV roof module combined with CIGS solar cell were described.

2. Experimental

2.1 PosMAC Steel Sheet

For materials used in this study, ternary alloyed PosMAC plated steel sheet (alloy compositions, Zn-1.6%Al-1.5%Mg; double-sided plating 120 ± 10 g/m^2) produced by #2CGL of POSCO STEELEON Co. Ltd were used to ensure corrosion quality even after more than 20 years of use for wall or roofing of buildings.

2.2 Thermal Dissipating Coating Solution

The thermal dissipating steel sheet was manufactured by performing a weatherproof coating with excellent thermal emissive as well as corrosion resistant properties on the front side where the solar module was attached, and a thermal radiation coating with excellent thermal emissive properties on the rear side. High-durable coatings were manufactured with the color of customer's preferred black series by adding thermal conductive pigment to polyester polymer resin with high crosslinking functionality to guarantee corrosion for more than 20 years. In addition, the former coating was manufactured by increasing the content of the pigment and lowering the composition of the lubricate wax so that the adhesion with the encapsulate film for attaching solar cells is excellent.

In order to give formability and thermal emissivity to the coating, the thermal dissipating coating dispersed a highly anisotropic thermal conductive pigments (transverse ratio ≥ 3; thermal conductivity 200-5000 W/m·K) to the polyester polymer resin with high crosslinking functionality. In addition, the content of acid-base hardening catalysts was adjusted to form wrinkles on the surface of the coating to maximize the surface area, greatly improving the heat dissipation characteristics [5,6].

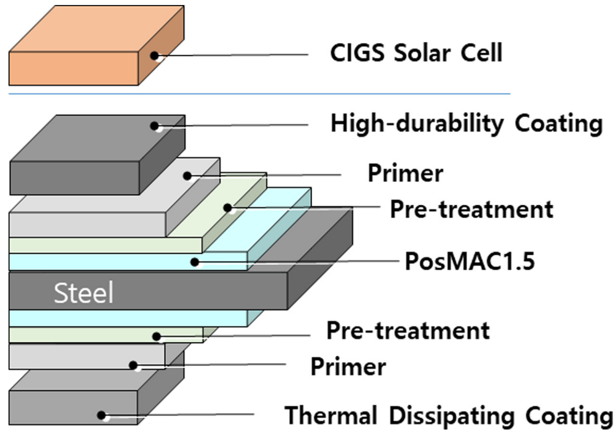

Fig. 1. Cross-sectional coating layer of thermal dissipating steel sheet; (front) high-durable coating, (rear) thermal dissipating coating

2.3 Preparation of Thermal Dissipating Steel Sheet

Manufactured from the #1CCL of POSCO STEELEON Co. Ltd., the front and rear of PosMAC plated steel sheet consists of pre-treatment, primer and top coating as shown in Fig. 1. The purpose of pre-treatment coating is to secure adhesion and corrosion resistance between the metal layer and the resin layer. After desorption and cleaning of plated steel sheets, Cr(VI) chromate solution ([Cr] 50 ± 10 mg/m^2) was treated in the roll coater (#1 Roll) and dried with hot air at 100 ºC. Primer coating is intended to cover up steel sheets and to give them corrosion resistance and desired color.

The pre-treated steel sheet was coated with a primer solution at a thickness of 5 ± 1 μm on the front and rear respectively during the roll-coating process (#2 Roll), and dried with a hot air so that PMT is 212 ± 5 ºC. The top layer was coated with the weatherproof and thermal dissipating coating solution at a thickness of 20 ± 5 μm on the front and rear respectively during the roll-coating process (#3 Roll), and dried with a hot air so that PMT is 232 ± 5 ºC.

2.4 Fabrication of BIPV Module

Two types of BIPV modules, flat and curved, using thermal dissipating steel sheets fabricated consisting of sections stacked with [steel sheet – encapsulant – CIGS cell – encapsulant – front sheet] as shown in Fig. 2. The encapsulant used TPO-XPO (thermoplastic polyolefin & crosslink polyolefin, 200 μm in thickness) film and front sheet used ETFE (ethylene tetraflouoroethylene, 300 μm

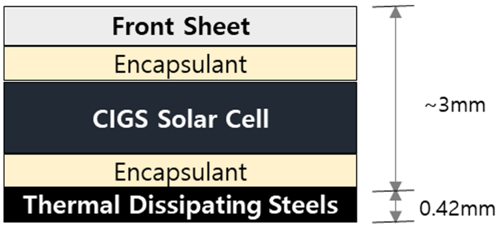

Fig. 2. Cross-sectional view of BIPV module

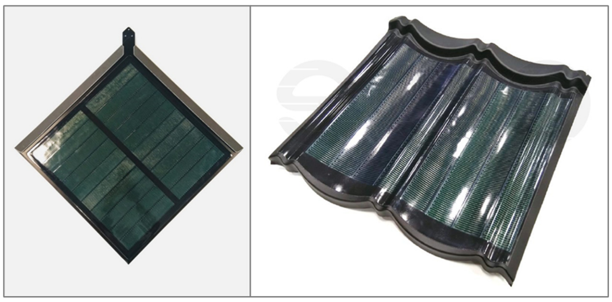

Fig. 3. Fabrication of BIPV roof module; (left) flat-type InterLoc model, (right) curved-type TwinTile model

in thickness) film. The BIPV module was manufactured by vacuum and compression treatment at an atmospheric temperature of 135 ± 5 ºC for 16 minutes after stack lamination of encapsulant, CIGS cell (MiaSole Flexcell), encapsulant, and front sheet on the thermal dissipating steel sheet. Meanwhile, curved module was manufactured by additional vacuum compression heat treatment at an atmospheric temperature of 110 ºC for 5 minutes in a pre-made mold (epoxy mold). The roof tile modules were produced in the same process as above by applying CIGS solar cells to flat InterLoc model (Roser Ltd., Korea [7]; Power 25 W, 18 Cell, 570 × 570 mm in size) and curved TwinTile model (RoofTG Ltd., Belgium [8]; Power 12.75 W, 6 Cell, 391 × 409 mm), in collaboration with Solliance Solar Research at the University of Eindhoven, Netherlands. The demonstration of durability and power generation efficiency of the BIPV module as shown in Fig. 3 is under way at the SolarBEAT outdoor test site at Eindhoven University.

2.5 Instrumentation and Evaluation Methods

The property evaluation of steel sheets were carried out using the following methods and instruments: The morphology and components of steel sheet' surfaces and cross-sections were analyzed using the optical microscope (Leica Microsystem) and the SEM (JSM-6610LV, JEOL Ltd.) devices. The pre-treatment coating quantity was evaluated by dissolving the steel sheet with a hydrochloric acid solution by wet method, and then quantifying [Cr] content using ICP (ICAP 6000 series, Thermo Scientific) equipment. The thickness of the primer and top coating layers was measured with SEM images and non-destructive portable gauges. The properties of the coatings were evaluated according to standard specifications. (pencil hardness, ASTM D3363; corrosion resistance, ASTM B117; bending formability, ASTM D4145; MEK (Methyl Ethyl Ketone) chemical resistance, ASTM D5402; acid resistance and alkaline resistance, ASTM D1308) Surface roughness was measured using a three-dimensional surface roughness analyzer (Leica Ltd., DCM8). Accelerated weather resistance was performed using the Q.UV_SE (Q-Lab.) device and evaluated the gloss retention rate of the coating layer after maintaining for 1000 hours, 8 hours at 60 ºC and 4 hours at 50 ºC for 1 cycle, in the ultraviolet wavelength area of type A (340 nm) and B (313 nm). The thermal emissivity of steel sheets was evaluated using the FT-IR spectroscopy (DIMAC M4500) as KS L 2514:2011 standard of the Korea Institute for Construction and Living Environment. The thermal dissipating properties were evaluated by making a box-shaped device (26 mm in thickness and 340 × 265 × 195 mm in size) simulating a solar module using an insulating material [9]. The measurement specimen (0.41 mm in thickness and 150 × 150 mm in size) with thermocouple attached was placed at the top of the test device and the temperature was measured on the inner temperature (T_A) of the box and both sides of the steel sheet (T_B, T_C), respectively. The heat dissipation temperature was evaluated by calculating the temperature difference of the coated steel sheet for the non-coated steel sheet as a reference after 60 minutes of measurement. Table 1 shows the results of the basic physical and quality evaluation of the coating film of the heat-dissipating steel sheet.

3. Results and Discussion

Recently the rise of the global environmental problem, the development of solar energy technology as an eco-friendly energy source is accelerating. In particular, a

Table 1. Results of quality evaluation for thermal dissipating steel sheet

-		Quality target	Evaluation		Evaluation standards
			Thermal dissipating coating	High-durability coating	
Coating thickness		22 ± 3 μm	23 ± 2	21 ± 2	· Portable gauge
Gloss		%	1.5	21	· ASTM G154 (angle 60º)
Corrosion resistance	plane	White rust (%)	0	0	· ASTM B117, SST 1,000 hr
	X-scribe	≤ 2 mm	≤ 1 mm	≤ 1 mm	· ASTM B117, SST 500 hr
Bending Test		No crack	No crack	No crack	· ASTM D4145, 0T-bending
Pencil hardness		≥ H	2H	2H	· ASTM D3363
Chemical resistance		No lamination	No lamination	No lamination	· ASTM D5402, Rubbing 100 times
Acid resistance		No blister	No blister	No blister	· ASTM D1308, dipping for 24 hr
Alkaline resistance		No blister	No blister	No blister	
Weather resistance	QUV-A	ΔE ≤ 3.0 / Gloss retention ≥ 70 (%)	0.7 / 84	0.4 / 86	· ASTM G154
	QUV-B		0.9 / 80	0.8 / 82	
Thermal emissivity		a.u	0.95	0.90	· KS L 2514:2011

building integrated solar module that combines building materials and solar cells into one is considered the most desirable model. It is estimated that BIPV technology will be widely distributed mainly in public buildings as the new and 'renewable energy 3020 policy' is established and implemented in Korea [10]. To this end, as mentioned in the introduction, the lightening of the BIPV module, the resolution of heat problems and the reduction of production costs are expected to accelerate further. As part of the solution to the above problem in this study, thermal dissipating steel sheet with excellent thermal emissivity was developed, and two types of light-weight BIPV modules applied to them were fabricated.

3.1 Thermal Dissipating Steel Sheet

Generally, metal has excellent thermal conductivity, but due to its poor thermal radiation characteristics on the surface, heat accumulates when used as a material for solar modules, resulting in a significant increase in surface temperature. Especially in summer, the surface temperature of the module reaches up to 90 ºC, so it is necessary to prevent the reduction of the power generation efficiency of the module through effective heat transfer and release of the material. For this purpose, the thermal radiation characteristics of steel sheet, which are materials for back sheet, can be improved to reduce the surface temperature of the module. The heat generated from the operating

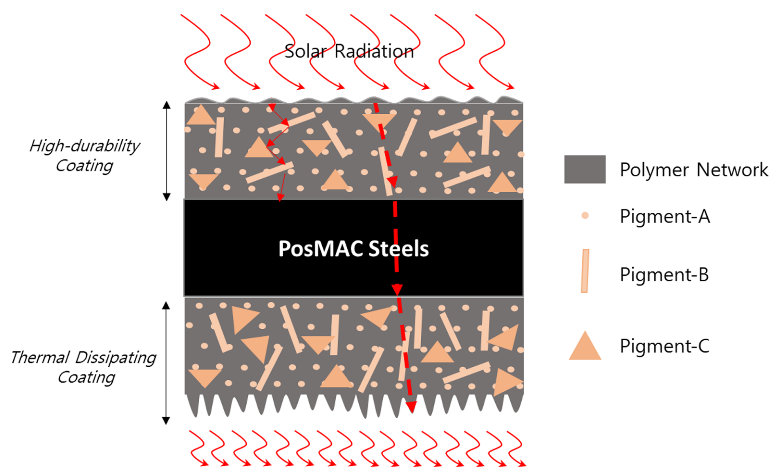

Fig. 4. Schematic diagram for thermal conduction of thermal dissipating steels

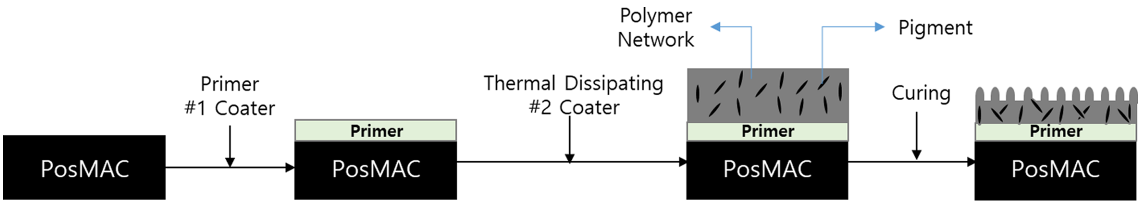

Fig. 5. Coating processes and wrinkle formation of thermal dissipating coating by curing reaction in the oven

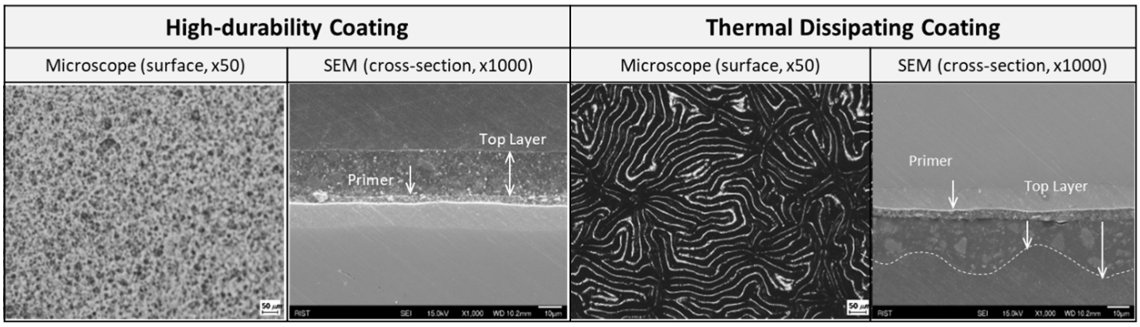

Fig. 6. Optical microscope and SEM images for front and rear coating layers of thermal dissipating steel sheet

temperature of the solar module is mostly infrared. In this area, the molecules that make up these materials, such as organic compounds, resins, and ceramics, absorb or release infrared rays in response to the molecular mode (stretching, vibration, bending) of covalent bonds and the lattice movement of ceramics. Thus, there is a method of using highly thermal emissive organic and ceramic additives in the coating as a way of giving high emissivity to the metal surface [11,12]. In this study, thermal emissivity of steel surface was improved by minimizing heat conductivity pathways as shown in Fig. 4 by using thermal conductive materials with large anisotropic properties to maximize thermal emissivity.

In addition, the heat radiation properties of the material are improved by the convection of the surface, so that wrinkles are formed during curing of the coatings to maximize the surface area. The coating is formed by a three-dimensional crosslinking between the polyester polymer, the main ingredient, and the amine curing agent. At this time, the dissociation of the amine-blocked acid curing catalyst added to initiate a curing reaction as it reaches a hardening temperature during the dry, resulting in a difference in the speed of the curing reaction due to differences in surface tension and inside the coating, which is different in volatility. That is, from the surface, solidification occurs first, and stress occurs on the surface of the coating due to the difference between the inside of the liquid and the surface's solidification. To relieve this, wrinkles are known to form on the surface of the film, as shown in Fig. 5 [5,6].

As a result of surface and cross-sectional analysis of thermal dissipating steel sheets, as shown in Fig. 6, high-durable coating layer is formed with a 20 μm in thickness of primer and a top coating, while has a flat surface. On the other hand, thermal dissipating coating layer had three-dimensional folds in the form of mountains and valleys, such as mazes in the range of 10 to 40 μm in thickness of primer and top coating. Wrinkles were significantly formed as the thickness of the coating layer increased (5 → 10 → 20 μm). The high-durable coating layer with no wrinkles formed have an average roughness of < 1 μm, while the average roughness of the thermal dissipating coating layer is in the range of 7 to 9 μm. This wrinkle formation, as mentioned above, is known to affect the size and density of wrinkles by the type, content, and size or content of the pigment, as well as the type and content of the amine blocked acid catalysts [5,6].

3.2 Thermal Properties of Thermal Dissipating Steel Sheets

Internal temperature was measured using a self-designed evaluation device to determine the effect of

Table 2. Measurements of inner temperature for diverse coated steel sheets depending upon coating layers

Steels	XX (Non-coated)	Pre-treatment (≤ 0.3 μm)	Primer (5 μm)	Termal dissipating (Rear, Primer 5 μm)			High-durability (Rear, thermal dissipating 20 μm)		
				5 μm	10 μm	20 μm	5 μm	10 μm	20 μm
Inner temperature (T_A)	72.9	72.3	70.0	67.8	66.7	66.0	62.6	62.4	62.1
ΔT (T_{XX}-T_A)	-	-0.6	-2.9	-5.1	-6.2	-6.9	-10.3	-10.5	-10.8

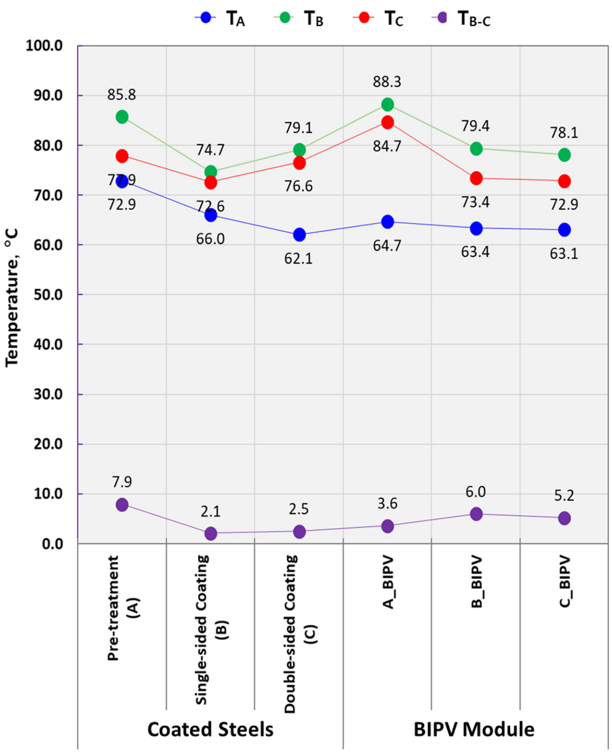

Fig. 7. Measurements of inner and surface temperatures for diverse coated steel sheets and BIPV modules

coating on heat conduction. In Table 2 and Fig. 7, the effect of coating thickness was relatively small, with internal temperatures of 67.8, 66.7, 66.0 ℃ and 62.6, 62.4, and 62.1 ℃ respectively, when the thickness of the thermal dissipating coating and high-durable coating layer was increased (5 → 10 → 20 μm). However, if single-sided coating and double-sided coating are performed compared to the reference specimen, the internal temperature is significantly reduced in the order of pre-treatment coating (ΔT = -0.6) < primer (ΔT = -2.9) < single-sided coating (ΔT = -6.9) << double-sided coating (ΔT = -10.8). This shows that the thermal dissipating characteristics are greatly improved by the coating. In addition, the thermal emissivity (front/rear) for each steel sheet was increased in the order of pre-treatment coating (0.58/0.58) < primer (0.79/0.79) < one-sided thermal dissipation coating (0.79/0.93) < double-sided thermal dissipation coating (0.87/0.93). This shows that the heat dissipation characteristics on the surface of the thermal dissipating steel sheet have been improved in the same way as the results of internal temperature measurements.

Internal temperature (T_A) and surface temperature at the front (T_B) and back (T_C) of the module were evaluated for BIPV modules with thermal dissipating steel sheets. In Fig. 7, the internal temperature of the pre-treatment steels, single-sided coating, and double-sided coating BIPV modules was 64.7, 63.4, and 63.1 ℃ respectively, which was relatively small. Meanwhile, the surface temperature (T_B, T_C) of the BIPV module was lowered in the order of pre-treatment coating, single-sided coating, and double-sided coating. This is due to improved thermal emissivity on the front and back of steel sheets.

3.3 BIPV Roof Module

In this study, the BIPV module with thermal dissipating steel sheet manufactured two models: planar and curved. The module applied the thermal dissipating steel sheet as a back sheet, and fluoride polymer film was used as a front sheet for durability and light weighting. The flat-type BIPV module is manufactured by cutting and pressing the thermal dissipating steel sheet and then stacking it on its surface in order of encapsulant material, CIGS solar cell, encapsulant and front sheet, then heating and pressing under vacuum. Meanwhile, curved modules create 3D CAD drawings for metal tile model (TwinTile) and then create 2D Die-cutter to cut thermal dissipating steel sheet, encapsulant and front sheet according to size. Subsequently, the module was manufactured by layering in order of thermal dissipating steel sheet, encapsulant, CIGS solar cell, encapsulant and front sheet, then heating and pressing under vacuum. The above modules were then adapted to the pre-made 3D epoxy mold, heated and pressed under a vacuum, and transformed into curved

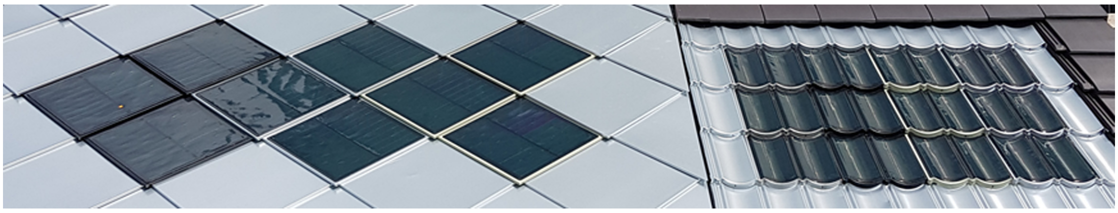

Fig. 8. Outdoor evaluation for BIPV roof module; (left) flat-type InterLoc model, (right) curved-type TwinTile model

shapes. The manufactured BIPV roof modules are being tested for durability, surface temperature, and power generation efficiency in collaboration with the University of Eindhoven's Solliance Solar Research as shown in Fig. 8.

4. Conclusion and Suggestions

Efforts are steadily underway to develop surface treatment materials with excellent thermal conductivity and radiation property for application to various sectors of the industry. It is predicted that BIPV roof tile modules that are applied with thermal dissipating steel sheets will be applied to buildings in the future as models of desirable renewable energy. In this study, thermal radiation properties were dramatically improved by treating thermal dissipating composite coating on Zn-Al-Mg ternary alloy plated steel sheet with excellent corrosion resistance applied to BIPV module. This is judged to be due to the improvement of heat conductivity in the coating by anisotropic thermal conducting materials and the improvement of thermal emissivity of the coating by implementing fine wrinkles on the surface of the coating. Compared to uncoated plated steel sheet, thermal dissipation properties have been greatly improved as the heat dissipation temperature has been greatly reduced when treating single-sided and double-sided heat dissipation coating. This is due to improved thermal radiation characteristics on the front and rear coating surfaces. The developed heat-resistant composite coating steel sheet was applied to fabricate two types of BIPV roof modules, both flat and curved. The module is manufactured by vacuum thermal compression method after stacking the thermal dissipating steel sheet, encapsulant, CIGS cell, encapsulant and front sheet in turn. In the ongoing outdoor evaluation, the BIPV module effectively discharges heat absorbed from the solar cell due to the effect of the thermal dissipating composite coated steel sheet used as a back sheet material, reducing the surface temperature of the module by 1 to 3 ºC on average compared to the reference material. Such a drop in surface temperature is expected to lead to improved power generation efficiency in the long-term use of modules.

It is also necessary to develop roll-to-roll module manufacturing technology to reduce manufacturing cost in order to significantly increase the spread of BIPV modules. The base technology for this is secured and by applying sequential stack of materials for BIPV and vacuum roll compression technology to thermal dissipating steel sheets, productivity can be dramatically improved to reduce manufacturing costs. In addition, technologies for the mass dissemination of BIPV modules require the BIPV design and appearance color as building materials that meet the diverse needs of customers. In line with the demands of the times, thermal dissipating composite coated steel sheets are expected to be responsible for the progress and mass supply of BIPV roof technology.

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