Heat Transfer Characteristics of Aluminum Sputtered Fabrics

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ABSTRACT

Al was sputtered onto four substrates: nylon, polyester, cotton/polyester, and shape memory polyurethane nanoweb, and the heat-transfer characteristics of the resultant materials were investigated by surface temperature measurements. The thickness of the Al layer increased linearly with sputtering time. The heat-transfer mechanisms of the multilayer systems in terms of conduction, convection, and radiation were investigated under steady-state conditions using a hot plate as a heat source in contact with Al-sputtered fabrics. The Al-sputtered fabric was placed on the hot plate, which was maintained at 35°C, and exposed to open air, which was maintained at 15°C. The temperatures of the air-facing surfaces of hot plate-Al-fabric-air (i.e., Al-phase-down) and hot plate-fabric-Al-air (i.e., Al-phase-up) systems were used to investigate the heat-transfer mechanism. It was found that heat dissipation to ambient air was much higher for the Al-phase-up system than for the Al-phase-down system. Heat-transfer coefficients of the Al surfaces were calculated and found to increase with the thickness of the Al layer. Furthermore, different conductive thermal resistances were observed for different fabrics prepared with the same Al-sputtering time. Consequently, differences in their thicknesses pore sizes, and thermal conductivities were suggested to have significant effects on their heat-transfer properties.

INTRODUCTION

Al is widely used to produce functional textiles owing to its high thermal and electrical conductivities [1, 2], good infrared reflectance [3, 4], and low cost [5]. The applications of Al-treated textiles include conductive textiles [3-5], flame-retardant textiles [6, 7], fire-fighters' protective clothing [8], and stealth clothing [9]. Accordingly, it is crucial to understand the thermal characteristics of Al-treated textiles that are used in protective equipment and personal heating appliances.

Heat transfer through textile substrates is known to be a complicated phenomenon. The temperature gradient between the human body and the ambient environment leads to heat transfer by conduction, convection, and radiation [10]. Heat transfer by a textile is significantly affected by its air content since air exhibits very low thermal conductivity [11]. When perspiration is taken into account, liquid water or moisture can be transported by means of diffusion, absorption, condensation, and wicking, which also involve heat release [12]. Thus, heat transfer in textile systems should be considered in terms of various factors such as the thermal conductivity of the fibers, fiber composition, cross-sectional shape, and thickness [10, 13, 14].

While numerous studies have been performed to investigate the effects of textile structure, few have addressed the effects of inorganic coatings on the thermal characteristics of composite textile materials. In a rare example, commercially available ceramic powders were added into a polyurethane film to enhance the thermal properties of warm-up suits, and this inorganic material coating was found to slightly increase the infrared emissivity and thermal resistance of the material [2]. Furthermore, Al deposition onto shape memory polyurethane (SMPU) nanoweb was found to increase its thermal resistance owing to improved body-heat reflection [1]. Moreover, heat-reflection by silver-nanowire-coated textiles contributes to their thermal insulation properties, and silver-nanowire-coating on both sides of cotton textiles enhances their human-body-heat reflectance by up to 40.8% [15]. This represents a dramatic improvement considering the 1.3% reflectance of the corresponding untreated textiles. It has been reported that thickness, density, and aerogel content are the most important factors for thermal insulation when coating nonwoven fabrics with aerogels [16]. According to Zheng et al.'s numerical prediction model for the heat-transfer properties of silicone-coated fabrics, yarn structure, weave geometry, and coating thickness are the important factors, and the authors' experimental results supported their prediction model [17]. However, despite these efforts, the role of inorganic coatings on the thermal characteristics of textiles is still not clearly understood, especially regarding nanostructured sputtering.

In this study, Al was sputtered onto different substrates, and the morphologies and thermal characteristics of the resultant materials were examined. In the case of nylon, the thickness of the Al-sputtered layer was controlled by the sputtering time. Furthermore, the heat-transfer mechanism in multilayer systems was analyzed theoretically and applied to an Al-sputtered nylon multilayer. Considering the importance of the heat convection of the surface facing the ambient air, the surface layer exposed to the air was varied and its effect was also investigated. Finally, the effects on heat transfer of the properties of fabrics prepared under the same Al-sputtering conditions were investigated.

EXPERIMENTAL

Materials

Nylon, polyester (PET), cotton/PET (50:50), and SMPU nanoweb are employed for the Al sputtering, and their characteristics are summarized in *Table I*.

TABLE I. Characteristics of base fabrics.

	Nylon	PET	Cotton /PET (50:50)	SMPU nanoweb
Weave type	twill (2/1)	plain	satin	Electro-spun web
Fabric count (warp x weft, in 5cm x 5cm)	148 x 67	206 x 173	83 x 75	-
Fabric thickness (μm)	177.4	65.3	554	89.6
Weight (g/m^2)	95.88	38.93	350.61	20.27

Nylon, PET, and cotton/PET (50:50) are commercially available fabrics. The SMPU nanoweb was prepared by the following procedure: *N*,*N*-dimethylformamide (DMF; Daejung Chemicals & Metals Co., Ltd., Korea) and tetrahydrofuran (THF; Daejung Chemicals & Metals Co., Ltd., Korea) were mixed at a ratio of 1:1 (*v/v*). Then, 14 wt% SMPU (MM3520, Diaplex, Japan) was added and the mixture was agitated at 300 rpm for 24 h at room temperature. Using an electrospinning apparatus (eS-robot® electrospinning & spraying system, Nano NC, Korea), the polymer solution was electrospun under an applied voltage of 16 kV, a tip-to-collector distance of 16.5 cm, and a flow rate of 1.5 mL/h [18]. A KES-F7 System (Thermo Labo II, Kato Tech Co., Ltd., Japan) was used to measure thermal conductivity. The thermal conductivity of nylon is 0.031 W/mK.

Al Sputtering

Using the metal sputtering equipment (SRN-120, SORONA, Korea), the Al was sputtered in pure argon atmosphere under 5×10^{-3} torr pressure at room temperature. The durations of Al sputtering were set 1, 3, 5, 10, and 25 minutes to control the thickness of the layer, and the Al was sputtered onto one side of each specimen.

Characterization

The surfaces of the specimens were observed using a field-emission scanning electron microscope (FE-SEM; JSM 7600F, JEOL, Japan). The image analyzing software Image J was used to determine the fiber diameters of the base fabrics and the thicknesses of the Al-sputtered layers from 10 points in the SEM images. Energy dispersive X-ray spectrometry (EDX, Aztec Oxford Instruments, UK) was used to analyze the surface chemical compositions of the specimens. To examine the relationship between heat-transfer phenomena and Al-sputtering conditions, an infrared thermal vision camera (FLIR i7, FLIR systems Inc., USA) was installed in an artificial climate chamber (Walk-in Environmental Test Chamber, EBL-5HW2P3A-22, ESPEC, Germany). To simulate an environment in which the human body would feel cool, the temperature and relative humidity in the climate chamber were maintained at 15°C and 50%, respectively.

In the hot-plate experiments, the temperature of the hot plate was set to 35°C. Thermal vision images were then captured from specimens placed on the hot plate. The fabric surface sputtered with Al was set either facing the hot plate or facing the ambient air.

To measure the far-infrared emissivity of each specimen, an FT-IR spectrometer (M2400-C, Midac Corporation, USA) was used. When measuring the emissivity, the sample collection area was fixed at 3 cm × 3 cm. The spectral range was 32–0.5 cm-1 at a resolution of 4 cm-1 and the final spectra were the averages of 32 scans at 37°C.

RESULTS AND DISCUSSION

Characteristics of the Al Sputtered Surfaces of Base Fabrics

Fabric surfaces before and after the Al sputtering were observed using FE-SEM, and the corresponding images are shown in *Figure 1*.

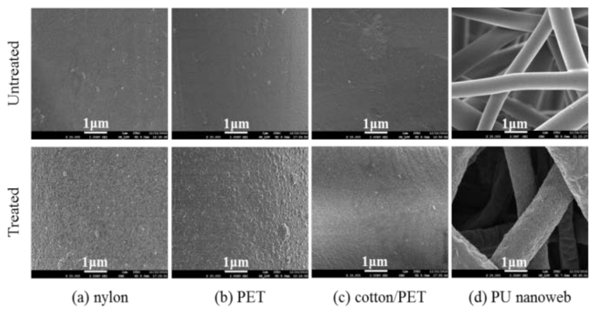

FIGURE 1. FE-SEM images of untreated and 10-min-treated samples.

The Al grains are coated uniformly onto the surfaces of all four substrates. As shown by the EDX results summarized in *Table II*, the percentage Al surface content detected for each substrate is different.

TABLE II. Chemical compositions of untreated and 10 min treated samples.

		C (%)	N (%)	O (%)	Al (%)
Nylon	Untreated	71.6	16.3	11.8	-
	Treated	19.6	2.6	22.1	54
PET	Untreated	71.7	-	28.3	-
	Treated	26.2	-	18.9	53.2
Cotton/PET	Untreated	72.8	-	27.2	-
	Treated	22.9	-	37.3	38.1
SMPU nanoweb	Untreated	76.7	7.6	15.5	-
	Treated	54.6	3.6	13.8	27.2

where *A* is the total surface area, *m* is mass, *d* is diameter, *l* is length, and *p* is the density of the fiber. As shown in *Table III*, the SSAs of the base fabrics are in the order SMPU >> PET > cotton/PET > nylon, and the Al surface contents increase in the order SMPU << cotton/PET < PET < nylon (*Table II*). Thus, it is assumed that a specimen having a higher SSA tends to have a lower Al deposition (except for cotton/PET). It is reasoned that cotton/PET fabrics have higher surface areas than the calculated values because the cotton/PET fiber is not a circular filament but instead ribbon-shaped.

Upon the completion of Al sputtering, the oxygen contents of nylon and cotton/PET increase, as shown in *Table II*. This might be caused by the formation of Al_2O_3 by partial oxidation of Al in the sputtered layer surfaces upon exposure to O_2 in air [21].

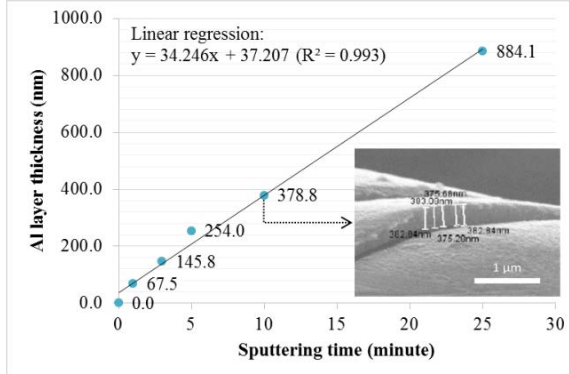

FIGURE 2. Al-layer thickness with sputtering duration (inset: cross-sectional image of 10-min-treated nylon fabric).

Thickness of the Sputtered Al Layer

Using nylon as the base fabric, the thicknesses of the Al layers were assessed following sputtering for different durations (1, 3, 5, 10, and 25 min). As shown in *Figure 2*, the thicknesses of the Al layers are 67.5, 145.8, 254.0, 378.8, and 884.1 nm, respectively. Thus, the thickness of the Al layer increases linearly with the duration of Al sputtering, as shown by the linear regression in *Figure 2*.

TABLE III. Calculated specific surface areas of the substrates used in this study.

	Density [20] (g/cm3)	Diameter (μm)	Specific surface area (m2/g)
Nylon	1.14	23.3	0.151
PET	1.39	10.5	0.274
Cotton/PET	1.47	13	0.209
SMPU nanoweb	1.25	0.9	3.556

Analysis of Multilayer's Heat Transfer Using Al- Sputtered Nylon

The base fabric and Al layer in the Al-sputtered fabrics have different thermal conductivities, thicknesses, and heat emissivities. The theory of heat transfer was thus employed to analyze the heat transfer through multilayer specimens in contact with a heat source, in this case a hot plate, at the steady state. This heat-transfer theory is illustrated in *Figure 3*, and was applied to Al-sputtered nylon with different Al-layer thicknesses. The heat-transfer rates were calculated for different specimen configurations (i.e., Al-phase-down or Al-phase-up) to determine the conformity of the experimental results with heat-transfer theory.

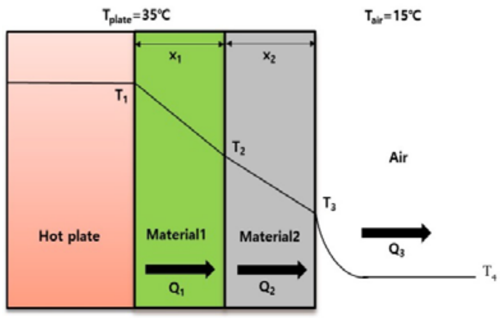

FIGURE 3. Heat transfer in a multilayer system.

The constant temperature of T_1 (35°C of the hot plate) and T_4 (15°C of the ambient air) and continuous heat flow from T_i to T_4 were assumed. Here, T_i represents the temperature of the interface between the hot plate and material 1 and T_2 represents the temperature of the interface between material 1 and material 2. T_3 denotes the temperature of the interface between material 2 and the air. The interfacial areas in the above system are assumed to be equivalent. The heat-transfer rates, thermal conductivities, and thicknesses of materials 1 and 2 are denoted as Q_1 and Q_2, k_1 and k_2, and x_1 and x_2, respectively. The heat-transfer rate from material 2 to air, heat-transfer coefficient, emissivity, and Stefan's constant are denoted as Q_3, h, e, and σ ($5.670 \times 10^{-8} \frac{W}{m^2 °C^4}$).

Here, the heat-transfer rate (Q_1) from the hot plate surface through material 1 via heat conduction and the heat-transfer rate (Q_2) of the heat conduction through material 2 are expressed in Eq. (2) [22]:

$$Q_1 = A\frac{T_1 - T_2}{R_1}\ ,\ Q_2 = A\frac{T_2 - T_3}{R_2} \qquad (2)$$

In Eq. (2), R_1 and R_2 denote the conductive thermal resistances of material 1 and material 2, respectively, and are defined as Eq. (3).

$$R_1 = \frac{x_1}{k_1}\ ,\ R_2 = \frac{x_2}{k_2} \qquad (3)$$

The heat transfer rate (Q_3) from surface of material 2 to the outer air can be expressed by convection and radiation components as shown in Eq. (4):

$$Q_3 = hA(T_3 - T_4) + \sigma\varepsilon A\left({T_3}^4 - {T_4}^4\right) = A\frac{T_3 - T_4}{R_3} \qquad (4)$$

where R_3 denotes the total convective and radiative thermal resistance, given in Eq. (5):

$$R_3 = \frac{1}{h + \sigma\varepsilon(T_3 + T_4)\left({T_3}^2 + {T_4}^2\right)} \qquad (5)$$

Since heat transfer at steady state was assumed in this study, all heat-transfer rate values are equivalent, allowing simplification to Eq. (6):

$$Q = Q_1 = Q_2 = Q_3 \qquad (6)$$

Thereby, Eq. (7) can be derived by substituting Eq. (2) and Eq. (4) for terms in Eq. (6):

$$Q = \frac{A(T_1 - T_4)}{R_1 + R_2 + R_3} = \frac{A(T_1 - T_4)}{\frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{1}{h + \sigma\varepsilon(T_3 + T_4)\left({T_3}^2 + {T_4}^2\right)}} \qquad (7)$$

In this study, we intended to apply the theory of heat transfer through such multilayers to analysis of the heat transfer through Al-sputtered nylon. The materials represented in *Figure 3* are nylon and Al, and the sequence changes depending on the face of the specimen exposed to air. The sequence was determined as hot plate-nylon-Al-air (Al-phase-up) when the surface sputtered with Al faced the air. When the surface sputtered with Al faced the hot plate, the sequence was hot plate-Al-nylon-air (Al-phase-down). These two configurations were employed for the heat-transfer simulation in this study to identify the effect of the arrangement of the Al-sputtered fabric on its heat transfer. To calculate the effects, the thickness (177.4 pm), thermal conductivity (0.031 W/mK), and emissivity (0.84) of the base fabric (nylon), and the thickness of the Al layer were obtained from measurements performed in this study. The thermal conductivity (205 W/mK) and emissivity (0.11) of Al were obtained from the literature [23, 24].

The temperature of the air was set to 15°C and that of the hot plate was set to 35°C. The surface area (A) was assumed to be 1 m^2.

To check that steady state was achieved, the surface temperature of 10-min-treated nylon was measured at different time intervals. As shown in *Figure 4*, the surface temperature is constant (± 1°C) after 1 min for both the Al-phase-up and Al-phase-down configurations. Consequently, temperature measurements were performed after the specimens were placed on the hot plate for 5 min.

The Al-sputtering time was varied to examine the effect of the thickness of the Al layer on the surface temperature. The surface temperatures of the specimens prepared with different sputtering durations were measured using an infrared thermal vision camera, and the results are shown in *Figure 5*.

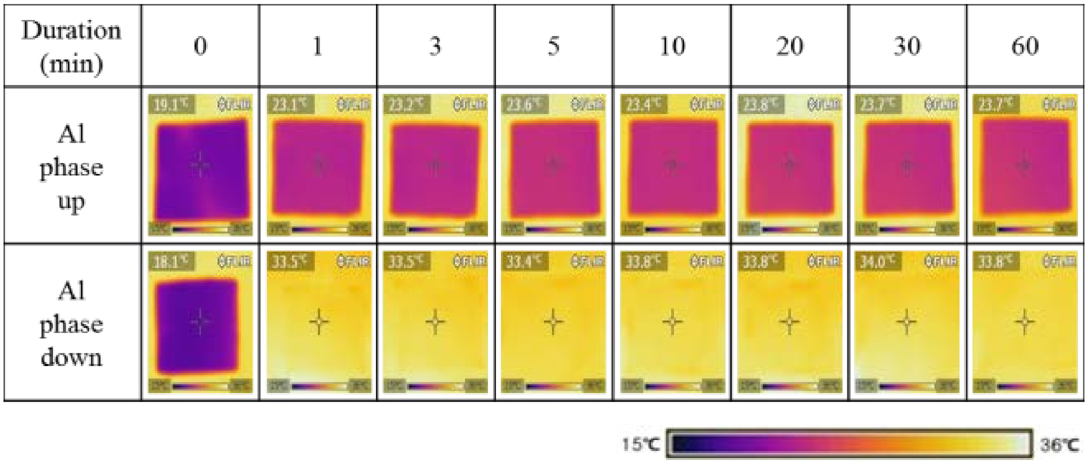

FIGURE 4. Infrared thermography of 10-min-treated nylon fabric after contact with the hot plate for different durations.

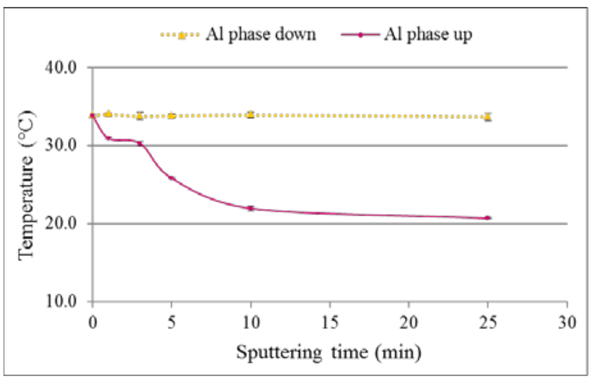

FIGURE 5. Surface temperature of Al-sputtered nylon according to the sputtering time.

For the Al-phase-up configuration, the surface temperature decreases from 34 to 21°C and approaches ambient temperature with increasing sputtering duration of from 0 to 25 min. Conversely, when the Al-phase-down configuration is employed, all the specimens show temperatures close to that of the hot plate, similarly to the untreated specimen. The standard deviations for all specimens are below 0.84°C.

When the Al-phase-up configuration is employed, the surface temperature decreases from 31 to 21°C as Al-sputtering time increases from 1 to 25 min. From analysis of these data, the heat-transfer coefficient (h) values of each specimen were calculated and are given in *Table IV*.

TABLE IV. Calculated heat-transfer coefficients (h) of Al-sputtered nylon fabrics.

Sputtering time (min)	1	3	5	10	25
Thickness (nm)	67.5	145.8	254	378.8	884.1
T_3 (°C)	30.7	29.9	25.1	20.8	20.1
Heat transfer Rate (W)	747.6	887.6	1709.8	2463.9	2576.1
Heat transfer coefficient (W/m^2K)	47	59	168	425	501

The heat-transfer rate (Q) was calculated by substituting the terms in Eq. (2) and Eq. (3) with the values for the thickness and thermal conductivity of the base fabric, i.e., nylon (177.4 pm and 0.031 W/mK) and with the values of the thickness and thermal conductivity of the Al layer (205 W/mK), including the measurements of surface temperature. The heat-transfer rate increases from 747.6 W to 2576.1 W and the surface temperature decreases with increasing Al-sputtering duration from 1 to 25 min. The heat-transfer coefficient (h) was calculated by substituting the corresponding terms in Eq. (4) with the measured surface temperature and calculated heat-transfer rate. Using this technique, the heat-transfer coefficients were predicted for Al layers with different thicknesses. For Al-phase-up, the thickness of the Al layer facing the outer air increases with increasing sputtering duration. Thus, the heat-transfer coefficient also increases, resulting in an increase in heat transfer by convection. Accordingly, the surface temperature of the Al layer facing the outer air approaches ambient temperature with increasing Al-sputtering duration. Although heat transfer from the

Al-sputtered surface to ambient air is influenced by radiation, it is much more heavily influenced by convection. Compared with the emissivity of the base fabric (0.84), the emissivity of Al (0.11) is significantly lower, allowing us to disregard the contribution of radiation. The heat-transfer coefficients of Al treated textiles increase as the sputtering time increases.

For the Al-phase-down configuration, the surface temperature (T_3) remains at approximately 34°C without significant change despite the increase of the sputtering duration from 1 to 25 min (*Figure 5*). Since the values of all the variables except T_3 in Eq. (7) are known, the value of T_3 was calculated through the trial-and-error method. The resulting value of T_3 was 34°C, which is similar to the measurement of temperature irrespective of the thickness of the Al-sputtered layer. The values of heat-transfer rate calculated from experimental results are in the range 171.05–171.06 W, which is an insignificant difference. Since the heat-transfer coefficient of the nylon facing the air is small and constant, the resulting heat-transfer rate becomes constant and small, and thereby the surface temperature of nylon would be similar to the temperature of the heat source. In particular, the convection and radiation resistances can be ignored because there is no air on the surface of the Al layer that contacts the hot plate.

Changes in the Surface Temperature of the Substrate with Al Sputtering

Nylon, PET, cotton/PET, and SMPU nanoweb substrates sputtered with Al for 10 min were prepared to identify their heat-transfer characteristics. As shown in *Table V*, the surface temperature was measured according to the surface facing the heat source or outer air.

For the untreated specimens, the surface temperature falls in the range 31.8–34.5°C regardless of the substrate. When the surface sputtered with Al faces the heat source, the surface temperatures also fall in the range 32.6–34.2°C, similar to that of the heat source. However, when the surface sputtered with Al faces the outer air, the surface temperature of cotton/PET sputtered with Al presents the highest temperature of 31.5°C, which is significantly different to those of for the other substrates. This difference in surface temperature was assumed to be attributable to differences in thickness, pore size, and thermal conductivity.

TABLE V. Surface temperatures (°C) of untreated and 10-min-treated nylon, PET, cotton/PET, and SMPU nanoweb for Al-phase-up and Al-phase-down configurations.

	Nylon	PET	Cotton / PET	SMPU nanoweb
Untreated	33.9	33.5	31.8	34.5
Al phase up	22.2	21.2	31.5	26.1
Al phase down	33.9	33	32.6	34.2

CONCLUSION

The heat-transfer characteristics of Al-sputtered textiles were investigated using surface temperature measurements. Al was sputtered onto nylon, PET, cotton/PET, and SMPU nanoweb, and the Al layer thickness increased linearly with sputtering time.

The heat-transfer mechanism of the Al sputtered nylon was analyzed by contacting the fabric with a hot plate. When the Al layer contacted the hot plate (Al-phase-down), the surface temperature was similar to that of the hot plate, regardless of the thickness of the Al layer. This is because nylon has a low heat-transfer coefficient. When the Al layer was open to the air (Al-phase-up), the surface temperature of the Al layer decreased significantly as the thickness of the Al layer increased. A plausible explanation for this phenomenon may be that the heat-transfer coefficient of the Al layer increases as its thickness increases. The high heat-transfer coefficient values indicate high heat convection at the surface for the Al-phase-up configuration. This increases the heat dissipation at the Al surface, resulting in a low Al-surface temperature.

When the heat transfer was assessed for all four kinds of Al sputtered fabrics, cotton/PET showed the lowest heat-transfer rate. In case of cotton/PET, the surface temperature for the Al-phase-up configuration was not significantly affected by layer thickness.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) (MSIP: No 2015R1A2A2A03002760), the Basic Science Research Program through NRF funded by the Ministry of Science, ICT & Future Planning (2016M3A7B4910940), and the BK21 Plus Project.

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