Development of Bionic Coating Technology to Enhance the Solar Heat Shielding Capability of Architextiles

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ABSTRACT

The current work developed a bionic coating technology that mimics the micro-hair arrays of Saharan Silver Ant (SSAnt) on the architextiles to enhance their solar heat shielding capability. To do so, the Al-ZnO microrods were synthesized via hydrothermal method and coated on the polyester fabrics in parallelly aligned way by a Meyer rod coating. The fabric properties coated with microrods were investigated with various tests. An outdoor solar exposure test was conducted to measure the solar heat shielding capability of the coated fabric. The diameter of the synthesized Al-ZnO microrods are about 0.8 - 2.6 μm and have a length of about 10 - 40 μm, which are similar in size to the SSAnt micro-hairs. The coated microrods are parallelly aligned along the fabric warp direction. The solar heat gain coefficient of the coated fabric is 23% lower than the original polyester fabric. The coated fabric has no degradation after exposed in simulated sunlight for 1440 hours. Under sunlight, the ground temperature covered by the microrods coated fabric is about 10 ºC lower than that of covered by the original Polyester fabric.

Keywords: Saharan Silver Ant, Bionic Coating Technology, Solar Heat Shielding Capability, Architextiles, Al-ZnO Microrods.

1 INTRODUCTION

The global high temperature in summer has become a serious public health threat, and therefore is very detrimental to the wellness and economy of the whole society. Fabric roof is a simple and low-cost solution to improve outdoor thermal comfort [1]. They are lightweight, flexible and portable, so they can be easily moved from one place to another, making them ideal for short-term special events in outdoor activities. However, current architextiles (textile fabrics for architectural use) have low heat shielding capability and have limited cooling effect. Therefore, it is very important to improve the solar heat shielding capability of architextiles for summer applications.

Saharan silver ants (SSAnt), insects living under extremely hot weather, show their amazing ability to keep cool. On hot summer days, they may reach maximal foraging activities when the temperatures of the desert surface are as high as 60 – 70 °C while their body temperatures are in the range of 48 – 51 °C, below their critical thermal maximum of 53.6 °C. This is achieved by their parallelly aligned micro-hairs [2-3], which not only enhance the solar heat shielding capability by reflecting visible light and near-infrared radiation in sunlight through Mie scattering and total internal reflection, but also enable efficient heat dissipation by increasing the mid-infrared emissivity. The strategy of mimicking SSAnt micro-hairs on fabrics has inspired us to develop a bionic coating technology to improve the solar heat shielding capabilities of current architextiles for efficient thermal management.

Our developed bionic coating technology consists of two steps: 1) synthesizing the Al-ZnO microrods as the artificial microhairs via wet chemical method; 2) coating the Al-ZnO microrods parallelly aligned on a polyester fabric with silicone binder via Meyer rod coating method. The fabric properties of the coated fabric were investigated by various experiments. An outdoor solar exposure test was also conducted to measure the solar heat shielding capacity of the coated fabric.

2 EXPERIMENTAL

2.1 Materials

Zinc(II) chloride anhydrous ($ZnCl_2$, Extra pure, DUKSAN) was stored in a vacuum chamber to avoid moisture after purchase. Nonionic surfactant Triton X-100 (100%, Sigma Aldrich), sodium hydroxide (NaOH, 99.9%, UNI-CHEM), aluminium isopropoxide ($C_9H_{21}O_3Al$, 100%, Sigma Aldrich), ELASTOSIL® LR 6200 A/B (WACKER) and silicone oil (50cSt, Magikmold) were directly used without further purification. The polyester (PET) fabrics were washed with AATCC detergent after purchase.

2.2 Synthesis of Al-ZnO microrods

The Al-ZnO microrods were synthesized via the modified wet chemical method by Pimentel et. al [4] under atmospheric pressure. First, a clear zinc ion solution was prepared by dissolving 0.371 M of $ZnCl_2$, 0.0185 M of $C_9H_{21}O_3Al$ and 8 M of NaOH into 20 ml of deionized water. Second, a Triton X-100 solution was prepared by dissolving 3 mL of Triton X-100 into 90 ml of deionized water. 11.78 ml of zinc ion solution and 88.22 ml of Triton X-100 solution were mixed in a polypropylene beaker. The mixture was cured with a hot air oven (Binder). The curing temperature was set to 100 ºC and the curing time was set to 20 hours. In order to reduce the evaporation of water, the beaker was covered with a polyethylene film. After that, the solution was naturally cooled down to room temperature.

The white precipitates were collected via centrifugation at the speed of 5000 rpm. To remove unreacted chemicals, the white precipitates were washed several times with deionized water and ethanol under ultrasonic and then recollected by centrifugation. Finally, the obtained Al-ZnO microrods were dried in air at 100 ºC for 4 hours.

2.3 Fabrication of bionic coating agent

Silicone oil was used as a diluent to reduce the viscosity of the liquid silicone rubber and to disperse the Al-ZnO microrods [5]. During the preparation of the coating agent, 5 g of Al-ZnO microrods were placed in 7 ml of silicone oil. They were mixed with vigorous stirring and were then dispersed with an ultrasonic disperser to form a stable coating paste. Some kieselguhr white was added in the coating paste to reduce the solution viscosity. The final paste ratio was: Al-ZnO microrods silicone oil: ELASTOSIL® LR 6200 A: ELASTOSIL® LR 6200 B: kieselguhr white = 2: 5: 5: 3. The coating agent was finally placed in vacuum to remove trapped bubbles.

2.4 Coating microrods onto the fabric via Meyer rod coating method

The as-prepared agent was coated on the PET fabrics via the Meyer rod method [6]. During the coating process, the agent was applied on a cleaned PET fabric with a Meyer rod (length: 23 cm, wire diameter: 100 μm) at the speed of around 1 m/min, and then the coated fabric was thermally cured at 130 ºC for 2 min.

2.5 Characterization

The fabric thickness and the fabric density were measured via standard test methods ASTM D1777-96(2015) and ASTM D3776, respectively.

The morphologies of the Al-ZnO microrods and the fabrics coated with the microrods were observed using a scanning electronic microscopy (SEM) (Leica Stereoscan 440, 20 kV). The samples were placed on a carbon tape and then sputtered with gold for about 2 min.

The solar heat gain coefficients (SHGC) of the fabric samples were measured to evaluate their solar heat shielding capabilities. SHGC is defined as the fraction of incident solar radiation transmitted through the fabric, both directly transmitted and absorbed and subsequently released inward [7]. It is expressed as a number between 0 and 1, and is calculated with the following formula:

$$\text{SHGC} = \frac{transmitted\ solar\ heat}{total\ incoming\ solar\ heat} \qquad (1)$$

In our tests of SHGC, the simulated sunlight (Newport, AM 1.5 G , Class ABB) was used as the light source and the incident light power was measured with a solar power meter (PMKIT-21-01 Newport).

The sunlight weatherability was measured by exposing the fabric sample to simulated sunlight in an accelerated weathering xenon arc weatherometer according to the procedure of ASTM G155. The test duration was 1440 h, i.e. 55 – 56 days of simulated sunlight exposure. The UV-VIS transmittance of the fabric samples before and after simulated sunlight exposure was evaluated by UV-VIS spectrophotometry.

The solar heat shielding capabilities of the fabric samples in outdoor applications were tested by exposing the samples to outdoor sunlight. Its experimental setup is shown in Figure 1. The ambient temperature was 26 - 27 ºC and the relative humidity was 35%. The cartons were used to prevent temperature fluctuations caused by wind and air convection. The fabric samples were placed above the cartons to block sunlight. During the experiment, the cartons were tilted toward the sun. A black foam was placed at the bottom of the carton to better absorb the unshielded sunlight. Therefore, the surface temperature of the black foam is used to express the ground temperature and is an indicator of the solar heat shielding capability of the fabric. A thermocouple in contact with the black foam was used to measure the surface temperature of the black foam. In order to evaluate the effect of our bionic treatment on solar heat shielding, two similar cartons covered by the original PET fabric and the polyethylene film as samples were constructed for comparison

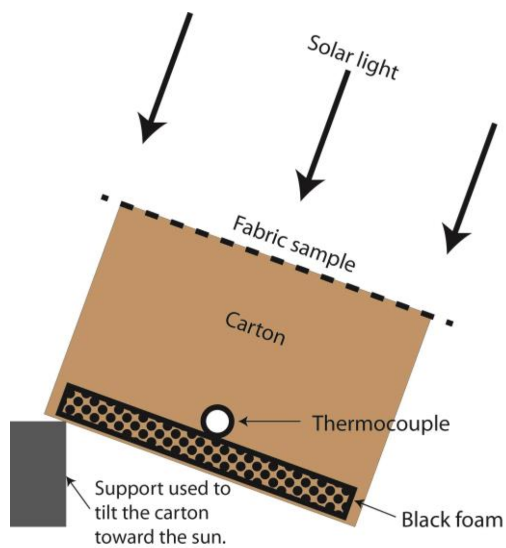

Figure 1: Scheme diagram of the experimental setup for outdoor solar heat shielding test.

3 RESULTS AND DISCUSSIONS

3.1 Morphology of Al-ZnO microrods

The surface morphology and grain size of the Al-ZnO microrods were investigated by SEM, as shown in Figure 2. They have a rod-type shape and are nonbranched. It clearly shows a hexagonal cross-section and a pencil-like tip. The size distribution of the Al-ZnO microrods was measured by analyzing with the software "imageJ". The diameters of the Al-ZnO microrods are about 0.8 - 2.6 μm while their lengths are about 10 - 40 μm.

We also analyzed the size distribution of Saharan silver ant micro-hairs and compared it with that of the Al-ZnO microrods. An SEM image of the head of the Saharan silver ant was searched from the paper by Shi et. al [2] and was analyzed with "imageJ". It is found that the lengths of Saharan silver ant micro-hairs are about 10 - 80 μm and their diameters are arround 1.9 - 2.8 μm. It implies that the Al-ZnO microrods as-prepared have a similar diameter distribution to the Saharan silver ant micro-hairs. Meanwhile, the lengths of the Al-ZnO microrods are within the size range of Saharan silver ant micro-hairs. Therefore, the Al-ZnO microrods with similar morphology of Saharan silver ant micro-hairs are successfully synthesized.

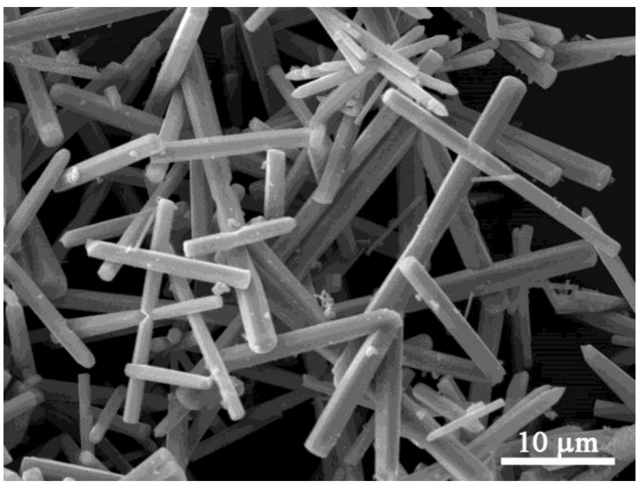

Figure 2: SEM image of Al-ZnO microrods.

3.2 Morphology of the thermal management fabric

The coating with microrods provides a white reflective coating on the PET fabric. The coated fabric is very flexible and can be bent easily without damaging the coating. The mass of original PET fabric is 262 g/m^2, while the mass of the fabric coated with microrods is 554 g/m^2. In other words, the fabric weight increases by 111% after the treatment. The microrod density on the fabric is 0.46 g/m^2. The average thickness of the fabric coated with the microrods is measured to be 0.55 mm, and the thickness of the uncoated fabric is 0.5 mm. The thickness of the coating is 0.05 mm and the standard derivation of the thickness is 0.015 mm.

The SEM image of the fabric coated with microrods is shown in Figure 3. It shows that the coating has a smooth surface. The Al-ZnO microrods (the light white bars in the SEM image) are well aligned. The density of Al-ZnO microrods in the SEM image is low because most Al-ZnO microrods are embedded in the coating and only a few microrods float on the surface. The results show that the parallel alignment of Al-ZnO microrods coating is achieved on the PET fabric to simulate SSAnt micro-hairs.

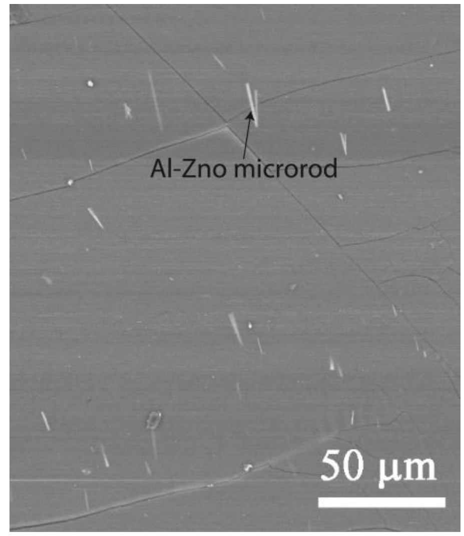

Figure 3: SEM iamge of the parallel alignment of Al-ZnO microrods coating on the PET fabric.

The alignment mechanism of the microrods within the coating is shown in Figure 4. The Meyer rod coating is very fast, up to 1000 ft/min. Because of the very short distance between the Meyer rod and the substrate, a strong shearing force is caused in the coating agent and directional alignment of the coating materials is usually resulted [8].

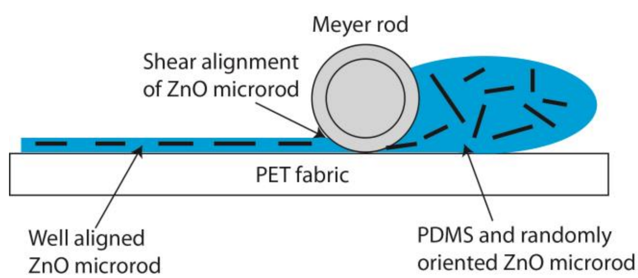

Figure 4: the alignment mechanism of microrods

3.3 Measurement of solar heat shielding capability

The SHGC of the fabric coated with microrods is 0.0327, while that of the original PET fabric is 0.0424. The SHGC decreases about 23% after coating the Al-ZnO microrods, implying that this coating on fabric can significantly improve its solar heat shielding ability.

The results of the outdoor solar heat shielding test are shown in Figure 5. The ground temperatures covered by the PET fabric coated with microrods, the original PET fabric, and the polyethylene film are 43.9 ºC, 53.2 ºC and 96.7 ºC, respectively. The ground temperature covered by the macrorods coated PET fabric is up to 10 ºC lower than that covered by the original PET fabric and up to 55 ºC lower than that covered by the polyethylene film. The microrods coated PET fabric also reduces the temperature fluctuation when the intensity of sunlight changes. This implies that the developed bionic coating technology can significantly improve the solar heat shielding ability of the coated fabric.

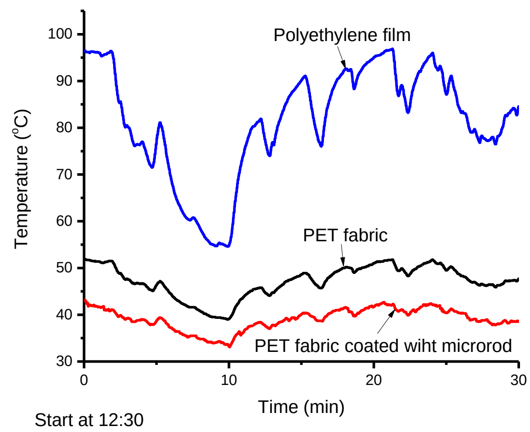

Figure 5: Results of the outdoor solar heat shielding test.

3.4 Sunlight weather resistance

The UV/Vis spectra of the PET fabric coated with microrods after the sunlight exposure test are shown in Figure 6. The sample after the 1440 h test has similar UV/Vis spectrum to the fabric sample before the weathering test. The results show that the fabric coated with microrods has very high sunlight weathering resistance.

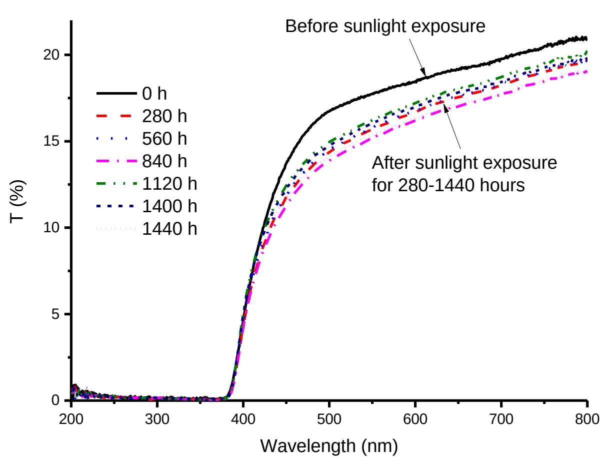

Figure 6: The UV/Vis spectra of the PET fabric coated with the microrods after sunlight weathering test.

4 CONCLUSIONS

A bionic coating technology mimicking the SSAnt micro-hair array was successfully developed. The Al-ZnO microrods synthesized via the modified wet chemical method have a diameter of about 0.8 - 2.6 μm and a length of about 10-40 μm, which are similar in size to the SSAnt micro-hairs. Via Meyer rod coating, the Al-ZnO microrods were aligned in parallel on the PET fabric surface along the coating direction. The SHGC of the fabric coated with microrods is 23% smaller than that of the original PET fabric. Under sun exposure, the ground temperature covered by the microrods coated fabric is about 10 ºC lower than that of covered by the original PET fabric, implying that the developed bionic coating technology can significantly improve the fabric's ability to block solar heat. The fabric coated with the microrods has no degradation after 1440 h of sunlight exposure. This is because the silicone binder has excellent sunlight weather resistance [9]. As a result, this bionic coating technology can be used to produce commercial architextiles with strong solar heat shielding capability, which will have a wide arange of applications, such as low-cost cooling roof .

5 ACKNOWLEDGMENT

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