Fashion and Textiles

RESEARCH



# Improved heating method for shape-memory alloy using carbon nanotube and silver paste

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**Abstract**

Shape memory alloys (SMAs) have a special ability to remember their initial shape and return from operating temperature. For this special ability, there are many studies in the field of smart wearables to replace rigid, heavy, and large electric actuators with SMAs that can be a fabrication. The usual operating method of the SMA is heating the SMA by direct Joule heating with electricity. Although direct Joule heating is fast and easy, there is overshooting, unstable, and high-power consumption. For these issues to use the SMA as textile actuators, this research suggested a heating method with silver paste required lower power consumption and coating the basic fabric with carbon nanotubes (CNTs) to support heating stability and heat uniformity. The heating method evaluated the efficiency of heat by comparing direct heating and silver layer heating and the uniformity of heat with the infrared images of whether CNTs coated or not. In this research, we reached higher temperatures with lower power than direct Joule heating using wearable heaters manufactured using silver paste. In addition, we confirmed that coating the basic fabric with carbon nanotubes reduce the temperature imbalance, and improved the heating stability. This research is expected that SMA will be used as a wearable actuator to help develop wearable devices that can move.

**Keywords:** Shape-memory alloy, Heating layer, Smart wearable, SMA textile actuator, Shape memory effect

## Introduction

A shape-memory alloy is an alloy that exhibits the shape-memory effect. The shape memory effect is used to bend a material with a martensite phase below a specific temperature and further return to its original shape with an austenite phase at a specific or higher temperature. A shape-memory alloy can store the desired form by heating an austenite structure at a high temperature and then rapidly cooling the structure. The shape-memory effect was discovered in 1932 (Ölander, 1932), and NiTi, a widely used shape-memory alloy, was discovered in 1963 (Buehler et al., 1963). According to the review of the shape-memory alloys research, it has high work per volume in actuator performance is 10 J/cm$^3$, are a factor of 25 times greater than the work density of electric motors and it can lift more than 100 times its weight (Jani et al., 2014). Because of these advantages of applying shape-memory alloys to the actuator, NiTi shape-memory alloys are used in various applications, such as medical devices, owing to their low cost, good physical properties, and safety. Furthermore, shape-memory alloys can be used as actuators with various designs using fabric (Gök et al., 2015), and the resilience of shape-memory alloys has been examined by embedding them in textile actuators (Chenal et al., 2014). Although common shape-memory alloys are irreversible actuators that can only one side actuate, they can be designed like yarns of the textile so that they are easily applied in the manufacturing process. When it is not actuating, its stiffness is like a thin wire that has a low resistance to clothing.

Generally, to actuate the shape-memory alloy, electric heating is used to operate shape-memory alloys (Shayanfard et al., 2019). However, when using conventional electric heating, the power consumption increases with an increase in the length or thickness of the alloy (Guan et al., 2020). Shape-memory alloys can operate only with the application of the operating temperature. When electricity is directly applied to an alloy, as the length of the shape-memory alloy increases, the consumption of electricity significantly increases to reach the operating temperature (Guan et al., 2021). This problem results in the limited use of shape-memory alloys.

When applied to textiles, both ends of the shape-memory alloy must be connected to the electrode by a conventional direct electrical connection. As the electric current flows through the shortest path, it hinders the operation of the shape-memory alloy. To overcome this problem, a different heating method must be applied to the shape-memory alloys used for the textiles. In addition, for the clothing industry, a variable that accurately represents the amount of heat generated is required, as the surface temperature must not exceed 50 °C according to Korea's electrical equipment safety standards. However, the resistance of the alloy changes owing to the change in the molecular structure during the operation of the shape-memory alloy (Guan et al., 2021). Even if the same current is applied to the shape-memory alloy, the amount of heat generated varies according to the change in resistance, which can lead to legal restrictions on the launch of clothing products.

The total amount of heat($Q$) produced by joule heating is followed by equation $Q = I^2R$. Where the Q represents the heat amount produced, $I$ is the current, and $R$ is the resistance. According to the Ohm's law, the voltage($V$) is followed by equation $V = IR$ and the power consumption ($W$) is followed by equation $W = VI$. According to these equations $Q = I^2R$ and $W = VI$, the total amount of heat is evaluated by the calculated power consumptions in constant current.

The silver paste can generate heat when a sufficient current is applied to it and using the silver paste by an electric heater can act as an excellent wearable heater owing to its fast operability, stability, and coating conveniences (Zhao et al., 2020). Therefore, in this study, a textile heating model is suggested and manufactured using the silver paste, to overcome the high-power consumption in electric heating as the length of the shape-memory alloy increases. In addition, there are studies that carbon nanotubes (CNTs) applied electric flexible heaters with their great electric and heat conductivity (Janas & Koziol, 2013; Lee et al., 2018). Referring to these studies, the CNTs are coated on fabric with a heating layer to support the silver paste and heat uniformly by heat conducting in a two-layered low-power SMA textile actuator. This study suggested the effective, stable, and low power consumed heating method with silver paste layer and CNTs coating to operate the SMA textile actuator and evaluated the heat efficiency of the method and uniformity of heat by comparing with direct heating and Infrared temperature image.

## Methods

### Equipment and specimen

The shape-memory alloy used in this study was a NiTi alloy. The experiment was performed using a wire (0.7 mm diameter) of the shape-memory alloy (SMA, Korea) with a Ni to Ti ratio of 1:1. Silver paste (DM-SIP-2001, Dycotec Materials, UK), which is a stretchable product, was used as the heating layer. The memory shape is fixed and it was prepared by heating it in an oven at 500 °C for 30 min and then rapidly cooling it at 10 ~ 30 °C for 30 min to store the shape.

### Production of heating layer using silver paste

The heating layer, which is used to heat the soft textile actuator, was produced by screen printing. The silver-paste path model was designed, as shown in Fig. 1a. This model was designed using Adobe Illustrator. An auxiliary sheet was cut using a laser and fixed to a fabric (basic nylon), which was further screen-painted. The fabric size was set to 150 mm × 50 mm (width × length), and then laser-cutting was performed. The screen painting was performed, as shown in Fig. 2, and the model was dried at 100 °C for 30 min. The trained SMA was fixed to the fabric by stitching.

### Testing of double-layer SMA actuator

The manufactured heating layer was tested, as shown in Fig. 3, using the B2902A Precision Source/Measure Unit of Keysight, in which the applied voltage and current are displayed. A constant current was applied, and the required voltage was obtained. Finally, the power consumptions and heat produced by Joule heating can be calculated by the power consumption equation. The surface temperature of the sample was obtained using a Fluke thermal imager (Ti105, FLUKE, USA).

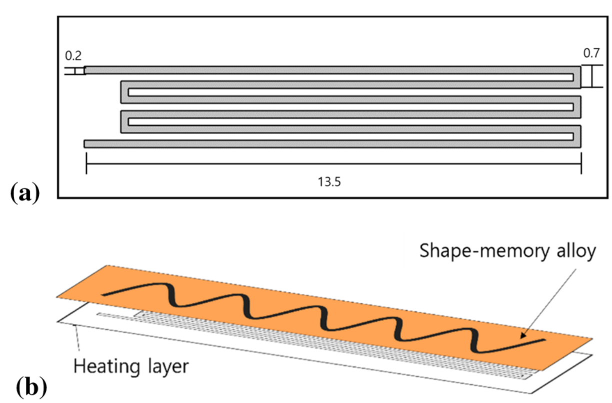


**Fig. 1** Design of silver-paste layer (**a**), double-layer heating system (**b**)

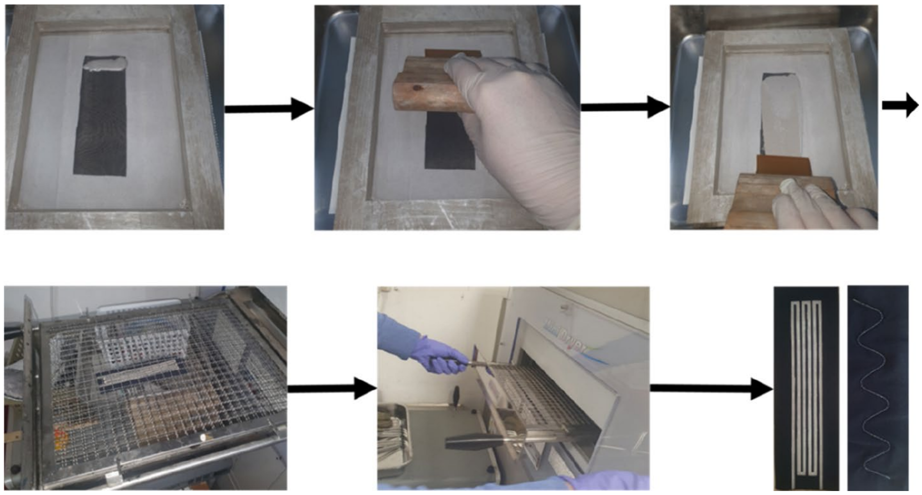

**Fig. 2** Screen printing silver-past layer

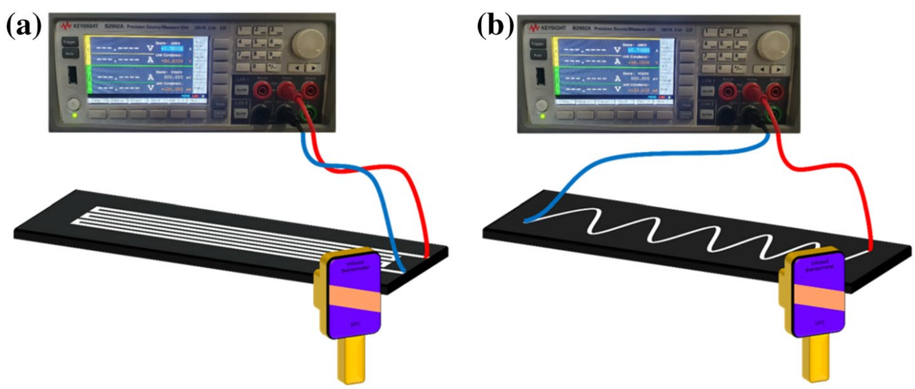


**Fig. 3** Testing of **a** heating layer model and **b** SMA direct

### Manufacturing a sample with improved heating efficiency by applying CNT to the fabric

CNTs have excellent electrical and thermal conductivities (Berber et al., 2000; Zhang et al., 2020). Therefore, a CNT was pasted onto the produced fabric sample, and the properties of the CNT were merged with those of the fabric. The padding was performed to put CNT inside of the base fabric. The dispersion liquid MEK(Methyl ethyl ketone) + MWCNT(Multi wall carbon nano tube) (purchased from Jenotube, Korea) was dried at 100 °C for 3 min, and the sample was produced in the same manner. Further, the produced sample was tested in the same manner. Figure 4 is manufacturing process of the applying CNT to the fabric.

## Results

### Produced sample and heating image

Figure 5 shows an image of the heating operation of the produced sample. As shown in Fig. 5, in the plain fabric, a defective factor was observed, in which the intermediate temperature of the sample largely differed from the average temperature. However, this

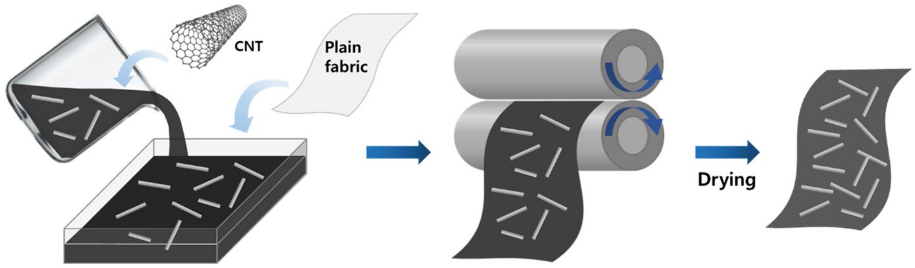


**Fig. 4** Manufacturing process of the applying CNT to the plain fabric

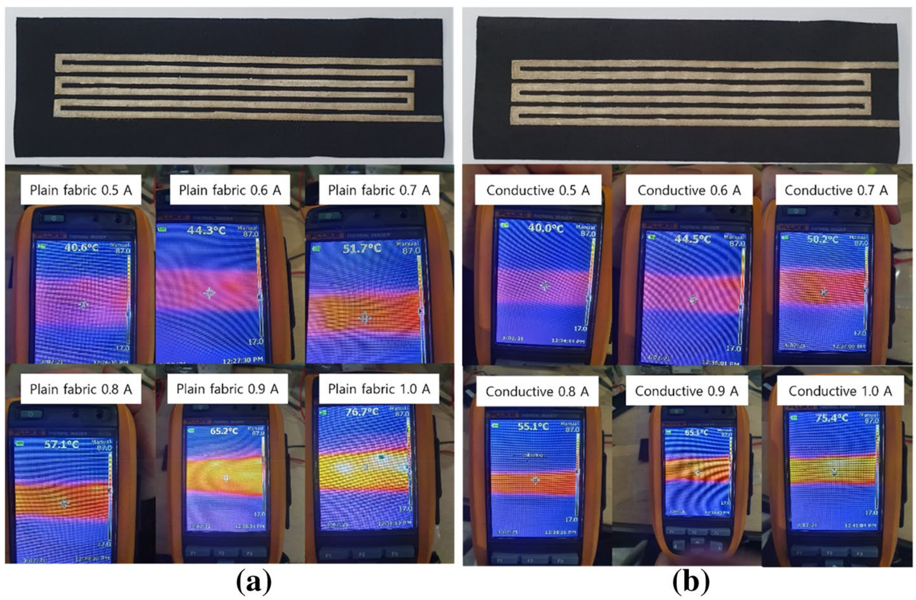


**Fig. 5** Test sample and its heating images at various magnitudes of applied current. Plain fabric (**a**), conductive fabric with CNT (**b**)

defective factor is some points not uniform heat was reduced in the conductive sample that underwent carbon nanotube (CNT) padding.

### Temperature dependence on power consumption of base fabric

Electric power is the product of voltage and current. As the electric power increases, the temperature increases. From Fig. 6, the heating layer prepared using the conductive fabric that underwent CNT padding reached a higher temperature at a lower voltage than the heating layer prepared with the plain fabric.

### Comparison between power consumption (W) and temperature (°C) during operation with SMA direct

The stored shape-memory alloy sample was tested. The current was increased from 0.5 to 1 A in steps of 0.1 A. The power (W) consumed and the change in temperature (°C) of the plain and conductive fabric samples were obtained under the same conditions and compared.

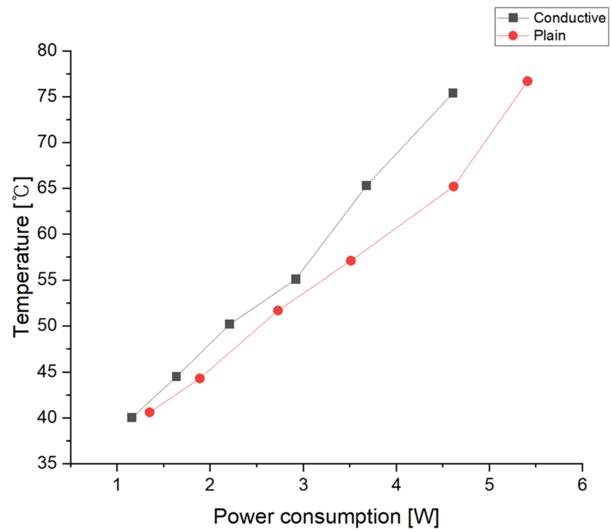


**Fig. 6** Temperature dependence on the power consumption of plain and conductive fabric samples

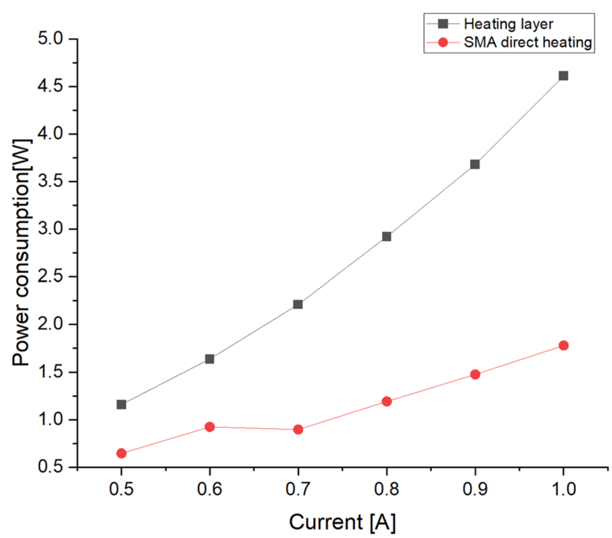


**Fig. 7** Power consumption dependence on the current in heating layer and SMA direct

## Discussion

The direct joule heating of SMA is lower power consumption than the SMA textile actuator with a heating layer in the 0.5 ~ 1A current range. According to Eq. (1), power consumption describes the total amount of heat produced. It can be evaluated to the efficiency of heating methods. As shown in Fig. 7, The heating layer much consumed power than SMA direct heating. Because the required voltage of SMA is lower than the heating layer by the resistance difference between metal and silver paste. As a result of this, Fig. 8 showed the temperature of the heating layer is higher than SMA direct heating. The difference in temperature between SMA and the heating layer is printed with silver paste shows 42.4 ℃ on 1A. It confirmed that this method is more

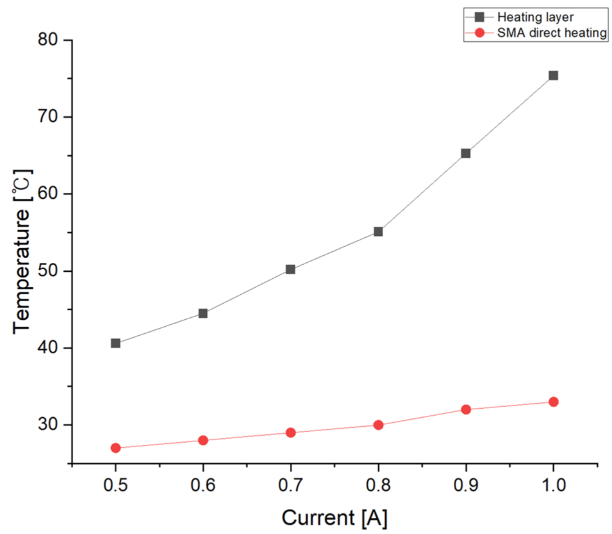


**Fig. 8** Temperature dependence on the current in heating layer and SMA direct

effective and suitable than direct Joule heating (Shayanfard et al., 2019) by comparing the temperature and power consumption.

To accurately actuate, the uniformity of heat is important in the whole SMA textile actuator. In this study, Coating the CNT into the base fabric works that supporting silver paste by Joule heating the entire area and conducting the heat. As shown in Fig. 5, the heated area of the sample that is without CNTs is not uniform. However heated area with CNTs is more stable and has no defect points which showed green. The heating layer that silver printed could heat samples to actuate SMA but it is only heated by the silver heating area so the heat couldn't be uniform. On the other hand, The CNTs make the entire area of the layer can be heated with silver paste printed area as shown in sample images of Fig. 5b. Because joule heating heat not only the silver heating area but also the CNTs with their conductivity. From the circuit point of view, the circuit is connected with silver paste and CNTs in a conductive fabric that makes the current flow separate. Although most current flows the silver heating layer, the other current flows the CNTs that also can heat the entire area. However, if the uniformity of heat is increased in this method can cause the layer to come into direct contact with the skin. This has a problem that electricity flowing through the heater is likely to flow into the human body. When applied to actual products and used for development, they should be designed separately so that they cannot come into contact with the human body to prepare for problems that may occur during direct contact.

## Conclusions

The purpose of this study is the more effective heating method for the SMA textile actuator which can be applied to smart clothes, wearable actuators, smart curtains, etc. Although its direct heating can be actuating fast it needs much power consumption which needs a bigger battery. The power consumption and temperature were lower for the direct connection than those for the heating layer. In the case of direct connection heating, as the resistance of the SMA changes for every measurement, the reached temperature and the applied voltage also change. Therefore, direct connection heating cannot be applied to the clothing industry, in which the reaching temperature must be limited. The sample produced in this study utilized indirect heating, and the reaction rate was slightly lower than that of direct connection heating, in which the core of the SMA is heated directly. However, in the case of SMA bundles or increased usage, a large amount of electricity was required so that power could not be applied to electrical devices suitable for wearable equipment. The heating layer is seen as a more suitable solution in terms of clothing utilization of SMA because it shows thermal efficiency in a larger area due to the same power consumption. Considering that the length of SMA in the prototype is greater than that in the experimental conditions and the length is longer, it can be said to be a more efficient operating module. Finally, in this study, the method of the indirect heating method with the silver pasted printing and applied CNT to the textile is more effective than direct heating for power consumption. However, for many applications, Future works should consider the heat protection method which is protecting the SMA actuating heat that can hurt the wearers.

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**Author contributions**
SJK and VCC originated the research idea. SJK collected data and drafted the first manuscript under the guidance of JYK, their supervisor. SUK contributed to developing the research design and the final manuscript. All authors read and approved the final manuscript.

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**Availability of data and materials**
The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests**
The authors declare that they have no competing interest.

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