Heating and Cooling Mechanisms for SMA Actuator - A Brief Review

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ABSTRACT Shape memory alloy (SMA) is a type of alloy with significant thermo-mechanical behavior that can be utilized as a solid-state actuator. However, the particularly useful thermo-mechanical behavior also highly non-linear and hysteretic. Making control of the SMA thermomechanical behavior exceedingly difficult. A highly controllable heating and cooling mechanism is the key factor to achieve good control of the SMA thermomechanical behavior. Thus, this paper reviewed the heating and cooling mechanism for the SMA intending to find a controllable heating and cooling mechanism for the SMA. A result from the review suggests that a mechanism with a combination of the thermoelectric module (TEM), a two-way mixing valve, and flexible tubing can offer temperature controllability for the SMA. This can be achieved by using the Peltier effect of the TEM to generate hot and cool liquid that can be channeled to the SMA in a tube through a two-way mixing valve to control the liquid temperature. Although this mechanism had been developed by the researcher, the optimization of the flexible tubing encasing the SMA to achieve maximum performance is still left poorly explore.

KEYWORDS: Shape memory alloy (SMA); Peltier effect; Resistive heating; Thermoelectric module (TEM); Artificial muscle
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Review Article

INTRODUCTION

SMA a solid-state actuator material with various applications especially in artificial muscle due to its high power-to-weight ratio (Kim *et al.*, 2019). However, the SMA mechanical properties are controlled through its temperature which required precise heating and cooling mechanism. The SMA thermomechanical behaviour is a highly non-linear and inherent hysteresis effect (Lee *et al.*, 2019). This makes the temperature control of the SMA exceedingly difficult. The use of the right heating and cooling mechanism is the key to the success of the temperature control system for the SMA.

Various mechanisms had been developed by researchers to control the SMA temperature in achieving the full manipulation of the SMA thermomechanical behaviour. This paper presents a review of these heating and cooling mechanisms and their advantages and disadvantages. This review aimed to ascertain a concept for the SMA actuator system with a temperature controllable mechanism for SMA thermo-mechanical manipulation.

This paper is structure into a few sections: Section 2 provide the basic working principle of the SMA. Section 3 present the commonly used resistive heating and its complementing cooling mechanisms. Section 4 discuss the use of TEM for the SMA temperature manipulation and its limitation. Followed by Section 5 on the liquid cooling and heating mechanism using the two-way mixing valve to achieve temperature control of the SMA that encased in a tube. Section 6 review the laser heating mechanism. In Section 7 a discussion is presented covering the heating and cooling mechanisms that had been reviewed in this paper. Lastly, in section 8 a conclusion of the review work is drawn with a direction of the advance of the heating and cooling mechanism for the SMA actuator.

WORKING PRINCIPLE OF SMA

SMA was first discovered in 1951 in an AU-Cd alloy material (Miyazaki & Otsuka, 1989; Jani *et al.*, 2014). However, SMA only becomes renowned after Buehler and Wiley invented a type of SMA called Nitinol in 1961 (Buehler & Wiley, 1965). Nitinol's thermomechanical properties are more superior compared to other SMAs, and this is the reason it has become renowned. Nitinol is an alloy with the composition of nickel (Ni) and titanium (Ti) with a certain ratio. The ratio of Ni and Ti in the alloy defines the thermo-mechanical behavior of the alloy. The thermo-mechanical behavior of the SMA exhibit a memory like a shape change corresponding to the temperature. The range of temperatures that induce mechanical properties changes in the SMA is referred to as the transition temperature. The Transition temperature can range from -100°C to 100°C based on the ratio of the Ni and Ti in the alloy.

The shape memory of the SMA is programmed onto it through a process called annealing. The annealing process requires withholding the SMA in the desired shape and heat it to a programming temperature that ranging from 350°C to 600°C and follows by a rapid cooling (Ikuta *et al.*, 1991). SMA that undergoes the annealing process will be able to perform shape memory effect by changing its temperature around its transition temperature. Lowering the temperature will cause the SMA to enter the martensite phase, where its molecular structure is in the form of monoclinic lattice. The monoclinic lattice molecule structure gives the SMA a low stiffness property. At low stiffness, the SMA becomes easily deform. By raising the SMA temperature to the transition temperature, the SMA molecular structure begins to absorb energy and turn into a body-centered cubic (BCC) lattice. SMA with BCC lattice is in the austenite phase. The fraction of austenite phase increase corresponded to the transition temperature. At the end of the transition temperature, the SMA achieves the full austenite phase. In the austenite phase, the SMA stiffness is 2 to 3 times higher than in the martensite phase. If no load is applied to the SMA, the high stiffness of the SMA will reform itself back to its memory shape (Song *et al.*, 2003; Williams *et al.*, 2010).

The thermo-mechanical behavior exhibit by the SMA is remarkably useful in many applications, these include automobiles, aerospace, building construction, biomedical, and robotic, specifically in the artificial muscle. Despite the advantages, SMA thermomechanical behavior also inherent hysteresis effect. The transition profile in Figure 1 illustrates the changes of Young's modulus, E from martensite to austenite and vice versa versus the temperature. In Figure 1, the E_a, E_m, M_s, M_f, A_s, and A_f are Young's modulus at purely austenite and purely martensite, the temperature at martensite start and martensite complete, the temperature at austenite start and austenite complete, respectively (Hashemi *et al.*, 2019).

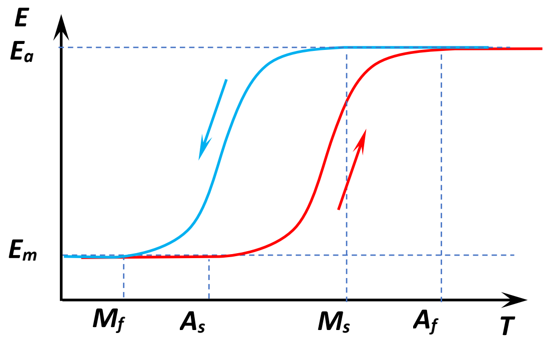

Figure 1. SMA Young's modulus versus temperature.

SMA thermomechanical property plays a very important role in the application of the SMA. The manipulation of the mechanical properties of the SMA required the precise control of its temperature. Due to the hysteresis and highly nonlinear thermo-mechanical behavior the mechanism to control the temperature of the SMA become difficult. This review discusses the mechanism used to control the SMA temperature and its implementation limitation and advantages.

RESISTING HEATING WITH NATURAL AND FORCE COOLING, AND OTHER COOLING METHOD

The most widely used heating method is resistive heating. The SMA is a conductive alloy with low resistance. Voltage can be supply across the SMA, based on Ohm's law the current is directly proportional to the input voltage and inverse proportion to the SMA resistance. The low resistance of the SMA will allow large current flow through it. The heat generated by the current is at the power of two of the current time the SMA resistance. To control the heat generation, pulse width modulation (PWM) can be used to control the amount of current and thus, control the heat generation. By controlling the amount of heat in the SMA means controlling the temperature of the SMA. This method can be observed in Guo *et al.* (2015), Hasan *et al.* (2016), Kim *et al*. (2019), Lara & Bersee (2015), Lee *et al.* (2019), Maffiodo & Raparelli (2017), Rodrigue *et al.* (2017), Song *et al.* (2016), Taylor & Au (2016), Villoslada *et al.* (2015).

To accomplish the current control, the power driver circuit can be used to control the current via the PWM signal. The resistive heating does not require a bulky heating element and simply controllable. However, this method is only good for heating and not cooling. If the speed is not a concern natural cooling is used but the cooling cannot be controlled. On the other hand, when speed is a concern, active cooling is normally applied.

Natural Air Cooling System

A natural cooling system uses heat convection to remove heat from the SMA in reducing the temperature. The natural cooling method is very subjective to the room temperature, the SMA temperature, the air change around the SMA. Cooling of the SMA via natural cooling is not consistent and cannot be controlled. This method is used mainly in the laboratory for proof of concept and no speed control is required. Such a system can be observed in research done by Guo *et al.* (2015), Hasan *et al.* (2016), Kim *et al.* (2019), Maffiodo & Raparelli (2017), Villoslada *et al.* (2015). The convection cooling becomes less effective if the SMA is encased in other non-heat conductive material to form a composite actuator. In these cases, the cooling process can be much slower (Lee *et al*., 2019; Rodrigue *et al*., 2017).

Active Air Cooling

An active cooling system is commonly achieved by increasing the airflow around the SMA. In Taylor & Au (2016) an electrical fan is used to directly blow on the SMA. To increase efficiency, a tube can be wrapped around the SMA wire and forced air is channeled through the tube creating high-velocity airflow to cool the SMA (Lara & Bersee, 2015). Meanwhile, Zhang *et al.* (2013) used an air jet produce from a jet nozzle using high-pressure air to cool the SMA. The active cooling method generally increases cooling speed, but the cooling process is difficult to be controlled. To slow the cooling, heating can be introduced during cooling. But this reduces the system energy efficiency.

Active Liquid Cooling

To further increase the cooling speed liquid cooler such as water is utilized. Peng *et al*. (2017) and Zhang *et al*. (2008) encased a bundle of SMA wire in a flexible tube and injected cool water into it to cool the SMA wire. Meanwhile, in Peng *et al.* (2017), Mascaro & Asada (2003) single wire is encased in a flexible silicon tube that is fabricated to the shape of the SMA for the cooling water to flow through the tube to cool the SMA. To improve the flexibility bellow shape of silicon encasement for a

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bundle of SMA had been observed (Taniguchi, 2013). All these designs use water flow rate to control the cooling rate and stop the flow during heating. Even though the water flow rate can be controlled, the fixed temperature of the cooling water will still give a sudden cool shock to the SMA. This will result in a non-controllable cooling process.

Other Cooling Methods

To increase the convection surface, heatsinks are applied by contacting the heatsink with the SMA during the cooling process. However, during heating, the heatsink will cause heat loss. Thus, in Russell & Gorbet (1995) a mobile heat sing that fixed on an antagonistic SMA actuated joint was designed. The heatsink is mounted on the joint and rotates with the joint toward the SMA that need cooling while the other SMA is heating in the antagonistic formation. This method improved the cooling process by providing a better convection coefficient. Due to the rectangular shape of the heatsink, the contact surface of the SMA and the heatsink is not linear and the cooling also dependent on the angular velocity of the joint. These make the cooling process complex and difficult to predict.

THERMOELECTRIC MODULE HEATING AND COOLING

The SMA heating and cooling process are both required to be controlled to fully gain full manipulation of the SMA thermomechanical behaviour. Resistive heating offers excellent heating but impediment by the cooling process. On the other hand, the thermoelectric module (TEM) can offer both heating and cooling via its Peltier effect. TEM with a high Peltier effect also known as the heat pump. It can pump the heat from one side to the other side, creating a heating side and a cooling side, and the heating and cooling side can be reversed by changing the polarity of the power supply. The SMA is placed in contact with the TEM for the heating and cooling process. Thermal paste can be applied to improve the heat convection. The use of TEM for heating and cooling can be observed (Yoong, 2018; Cho & Asada, 2006). In Cho & Asada (2006), the heating and cooling are segmented using deferent sized TEM some on each SMA wire and some shared with few SMA wire, where each SMA wire is actuating one finger to create the cascading effect of the human fingers.

The TEM having a flat surface made from ceramic had limited shape for the SMA to lay flatly on the TEM. Generally straight or snake shape annealed SMA can be used on the TEM for heating and cooling. The use of TEM cannot accommodate the spring coil-type SMA actuator due to the geometrical constraints.

LIQUID HEATING AND COOLING

Due to the geometrical constrain of the TEM, TEM or some other means of hot and cool liquid generation can be used externally to supply heat to the SMA via tubing. A containment layer made from soft or flexible material is used for encapsulating the SMA and to contain the liquid, and ensure the liquid keeps contact with the SMA wire. In Ishikawa & Nakada (2010), a contractable rolled film tube is used to encase the SMA wire forming an artificial muscle. The rolled film tube provides a barrier for the liquid that contacts the SMA from mixing with the inert liquid around it. Due to the rolled film tube is not leakproof thus, the whole SMA actuator is submerged in the inert liquid. Hot and cool water are channeled into the rolled film tube to control the temperature of the SMA. Instead of using a rolled film tube, Park *et al.* (2019), Park & Son (2017) used a flexible silicon tube to fully seal a bundle of spring-shaped SMA wire. Liquid with the desired temperature is channeled through the silicon tube to control the SMA temperature. A two-way mixing valve is used to bland the hot and cool water to the desired temperature before channeled into the silicon tube to control the SMA temperature.

Instead of using a flexible tube, Hegana *et al.* (2015) used a hard channel with a top opening for an antagonistic pair SMA actuators. The bottom part of the tube and SMA is fixed. The top end of the SMA is connected to a joint in the antagonistic formation. Like Park *et al.* (2019), a two-way mixing valve is used to feed liquid with the desired temperature to control the SMA.

LASER HEATING

Laser heating is uncommon for SMA heating especially in large actuators such as artificial muscle applications. This is due to the SMA is having dimensions like human structure. The large SMA actuator requires a lot of laser sources to cover it. Laser heating is applied to a miniature SMA actuator. The high-power density and controllable laser intensity provide fast and precise heating control on the miniature SMA. Similar to resistive heating the cooling mechanism is absent in the laser heating system (Knick *et al.*, 2019; Lee *et al.*, 2018). However, the miniature SMA actuator is small and the heat amount store in the SMA can be released to the environment in a truly short time. With the fast heating from the laser and fast natural cooling, the miniature SMA actuator still can achieve particularly good bandwidth.

DISCUSSION

The commonly used resistive heating on the SMA actuator had been impaired by the absence of a cooling system. Attempt to mitigate the setback of a resistive heating system, both active and passive cooling systems using air and liquid had been introduced by various researchers. Flexible tubing had been applied to encase the cooling liquid and provide a better-controlled environment during the cooling of the SMA. But the results of these cooling systems are yet to achieve satisfactory cooling control. Few researchers used TEM to provide both heating and cooling for the SMA actuator. But the SMA shape is limited by the physical constrain of the TEM. The common spring shape cannot be directly used on the TEM. Additional flexible tubing is used to encase the SMA and channel hot and cool water into it to control the SMA temperature. The hot and cool water can be generated using TEM or using other methods. The encasement develops by the researchers is bulky and has a large gap between the SMA and the encasement wall. The large gap will require a large volume of liquid to fill up and this reduces the operating speed and require more energy to operate. Lastly, the laser heating method had shown fast heating, but it had a similar problem like the resistive heating, and it is not practical for large size actuator.

The TEM had shown promising application with the couple to the SMA for temperature control. The used of tubing to channel the hot and cool liquid to the SMA via a two-way control valve solved the geometrical constrain of the TEM. However, the existing tubing system is bulky and can cause the actuator to have low bandwidth. Thus, optimizing the tubing system for the SMA can be a research gap that requires a detailed investigation.

CONCLUSION

The heating and cooling mechanisms for the SMA actuator had been intensively review in this paper. The review found the extensively used resistive heating shown major setback in the cooling process. Meanwhile, the TEM usage in manipulating the SMA temperature can be enhanced by using tubing to channel the hot and cool water to the SMA without the need to keep the SMA in

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contact with the TEM. The use of tubing had revolted the limitation of the TEM geometrical constrain. The existing tubing system is still at the initial and proof of concept stage. The next level of investigation is essentially needed to optimize the tubing mechanism.

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