Study of Shape Memory Alloy De-icing Device for Non-rotating Components of Aircrafts

Xin Liu*, Yuming Xing, Liang Zhao

School of Aeronautic Science and Engineering, Beihang University, Beijing 100083, PR China

*Corresponding author e-mail: liuxin900320@buaa.edu.cn

Abstract. Shape memory alloy (SMA) is a promising material which has widely been applied in aerospace industry. Its unique nature of the high stress output rate and low power requirement agrees the need of energy saving in aircraft de-icing. Among the few designs of the SMA de-icer, Gerardi’s project for rotating blade is more fit to the requirement of the de-icer for aircrafts. However, it is not clear that if the de-icer is capable to de-icing for non-rotating components or not. In this study, design of the SMA de-icer for non-rotating components were presented. Characteristics of the SMA de-icer and factors influence on it were confirmed by numerical methods. The major results show that the SMA de-icer can achieve de-icing objective well. De-icing rate of 100% can be obtained. For the designed SMA de-icer, pre-strain of 4% of the SMA sheet is recommended. Thinner SMA sheet helps greatly improve de-icing performance of the SMA de-icer.

1. Introduction

In-flight icing is a major hazard which threatens flight safety and has caused several accidents [1]. Slight ice deposition on engine struts, the first few compressor stages and cap will lead to drastic flow distortion which can affect engine performance and stability seriously [2]. Many ice removal systems aimed at aero-engine air intake system have been researched. These ice removal systems can be classified into de-icing system and anti-icing system [3]. However, all of the anti-icing systems employ heat to prevent ice formation. Thus, they are energy-intensive. To achieve the object of low power, de-icing system is preferred rather than thermal heating systems [4]. Several attempts have been carried on for a low power de-icing device. For example, the electric impulse de-icing system [5], the ultrasonic de-icing system [6,7], the dielectric barrier discharge plasma de-icing system [8] and so on. However, in the de-icing systems mentioned above, extra equipment is introduced to keep the systems running smoothly. This adds extra weight on the aircraft, which is not expected.

The SMAs are approved a promising material due to its low-weight and high stress output characteristic and have been used widely in the aerospace industry. On the application of SMAs for aircraft de-icing, only few researchers reported their de-icer designs and the validation results. Gerardi, Ingram and Catarella presented a preliminary design for a SMA-based de-icing system for helicopter. Their design used a NiTi SMA sheet which showed different performance in the whole sheet to remove ice deposit on the rotor blade [9]. A composite material with SMA wires embedded inside was designed for leading edge de-icing by Herrero [10]. Static de-icing experiments were implemented in their
laboratory. The device could shed ice successfully. In 2013 University of Maryland undergraduate student Righi et al presented a design for rotor blade de-icing with NiTi SMA Wires connected to a thin aluminium shaped as the leading edge of a NACA0012 airfoil [11]. The experiment validated the effect of the designed de-icer.

In this paper the design of the de-icer utilizing the NiTi SMA sheet is proposed and the characteristic of the designed de-icer is investigated numerically. The main purpose of this paper is to validate the de-icing performance of the SMA de-icer for non-rotating structure on aircraft and aero engine. The structure of the manuscript is organized as follows. In Section 2, the design of the SMA de-icer is presented. Simulation and analysis of the SMA de-icer is presented in Section 3 and section 4. Then, the major conclusions are presented in Section 5.

2. Design of the SMA de-icing device
The schematic diagram of SMA de-icing process is shown in Figure 1. Ice is allowed to build on the de-icer surface. Then, the SMA de-icer is activated to pull the sheet which the ice is built on. When the forces generated by the sheet exceed the adhesive force of the ice, the ice sheds from the icing surface.

![Figure 1. SMA de-icing mechanism [9]](image1.png)

![Figure 2. The structure of the SMA de-icer](image2.png)
Three design issues need to be considered to incorporate the SMA into a de-icing system. The first one is to determine the mechanical requirement for breaking the adhesive force of the ice. The issue decides what kind of SMA should be chosen. The second one is to determine the transition temperature range, which implies the power requirement. The third issue is to determine the SMA restraining mechanism. The restraining mechanism decides the circulation reliability to make the de-icing system work circularly. In addition, the designed de-icer should be highly durable, aerodynamically non-intrusive, and a proper power requirement.

The SMA based de-icing system is designed considering the aforementioned issues. A SMA de-icer was designed to validate the effectiveness of the SMA de-icer. The structure of the test article is shown in Figure 2.

The SMA de-icer consists of four parts, namely the SMA sheet, the silicone pad, the base and the heaters. The SMA sheet has two functional regions: the actuator area and the icing area. Ice is allowed to build on the icing surface, then the SMA actuator contracts when it is activated by the heaters. The icing surface strains and shears off the attached ice. The SMA transfer temperature range is set as 50℃ -70℃ to avoid the de-icer self-activate. As-rolled NiTi material is chosen as the SMA sheet in the de-icer due to its good processing characteristic and outstandingly elastic performance. The as-rolled NiTi sheet is capable of 4% elastic strain which satisfies the restrain requirement of the de-icer. Thus, it is the ideal choice of the icing surface. To avoid the risk of joint failure between the icing area and the SMA actuator, the SMA actuator and the icing surface are built into a single as-rolled NiTi sheet by converting both ends of the sheet with shape memory effect. The ratio of the SMA area and icing area is 3:7. The schematic diagram of the as-rolled NiTi sheet is shown in Figure 3. The silicone pad is under the SMA sheet which is used to supply enough elastic space when the icing area strains. The electric heating pads are employed as heaters to activate the SMA actuator. In present paper, a 24V, 2A power source are used.

![Figure 3. Functional parts on the Ni-Ti sheet](image)

3. Simulation analysis of the SMA de-icer

3.1. Numerical methods

In this paper, we consider the special mechanical-thermal characteristic of SMAs as a behavior named as thermal shrinkage effect. It can be described as that the SMAs recover when it is heated to specific temperature. The 1D kinematic model is employed to approximate SMAs behavior in different stage as following:

\[ \varepsilon = \alpha \Delta T \]  

(1)

Where \( \alpha \) is the thermal expansion coefficient in present paper, value of \( \alpha \) is obtained by a test of the NiTi SMA sheet. Three pre-strains were tested.
The pyroclastic model is employed to describe the behaviour of the adhesive ice [12]. In this model, it considers the effect of ice temperature on the mechanical characteristic of the adhesive ice. The details of the model can be found in reference [12].

Failure criterion of the adhesive ice is the key model to evaluate the de-icing effect of the SMA de-icer. Labeas et al [13] proposed an ice failure model considering the principal and shear stress which is written as:

\[
\left( \frac{\sigma_{\text{max}}}{\sigma_U} \right)^a + \left( \frac{\tau_{\text{max}}}{\tau_U} \right)^b \geq 1
\]  

Where \( a = 1 \) and \( b = 2 \). The value of the \( \sigma_U \) and \( \tau_U \) is 1.44MPa and 0.4MPa, respectively.

3.2. Computational geometry and boundary conditions

The basic structure of simulated de-icer is mentioned in section 2. The heaters and the rivets are neglected in the simulation. The de-icing zone of the de-icer is considered as the simulated model because this zone is the main functional zone of the de-icer. The size of the de-icer for simulation is shown in Figure 4. The leading edge of the de-icer model is a semicircle which has a radius of 25mm. The simulated model has a length of 55.73mm. This region stands for the de-icing zone of the de-icer. The width of the de-icer is 100mm.

![Figure 4. Schematic of the simulated model](image)

In the simulation process, the basement is considered as entity. And the SMA sheet is treated as shell. The hexahedral entity mesh is used for the basement and the triangular shell mesh for the SMA sheet.

As mentioned in section 3.1, the behavior of the SMA actuators in this paper is simplified as heat shrink effect. The heat shrink coefficient of the present SMA actuators is obtained by experimental means. In this work, the shrink effect is implemented into the computational code as a strain boundary condition. Zero-displacement boundary condition is used for the basement. And the interaction between the basement and the SMA sheet is considered as the tangential frictional behavior. The friction coefficient is 0.12.

To evaluate the performance of the SMA de-icer and the influence of different structural parameters on characteristics of the de-icer, several cases were implemented. The simulation conditions are listed in Table 1. SMA Pre-strains of 3%, 4% and 6% were considered because these pre-strains are common in application of NiTi SMA Sheet as actuators. Three kinds of thickness are set to analyse the influence of thickness on the performance of the de-icer.
Table 1. Simulation conditions

| Case | Pre-strain (%) | SMA sheet thickness (mm) | Temperature of the adhesive ice (K) |
|------|----------------|--------------------------|-----------------------------------|
| 1    | 3              | 0.15                     | 254                               |
| 2    | 4              | 0.15                     | 254                               |
| 3    | 4              | 0.5                      | 254                               |
| 4    | 4              | 1.0                      | 254                               |
| 5    | 6              | 0.15                     | 254                               |
| 6    | 4              | 0.15                     | 240                               |

4. Results and Discussions
To ensure the de-icer can work circularly, plastic deformation is forbidden in the SMA sheet. In addition, enough strain output of the SMA sheet is required to achieve the goal of de-icing. Thus, the stress in the SMA sheet is investigated firstly. Figure 5 shows the simulation results of stress in the SMA sheet with different pre-strains.

From the results in Figure 5, we can see that the stress increases from the leading edge to downstream of the de-icer. Then, the stress decreases rapidly at the location of about 30mm. after the rapid decline of the stress, it increases slowly again. The reason of the obtained results is because there is a transition from cylinder to plate at location of Y=25mm. Thus, the stress experiences a rapid decline in this geometry form. The stress results in the SMA sheet pulled by the actuator with pre-strains of 3%, 4% and 6% are also compared in Figure 5. The results indicate that the stress in the SMA sheet shows the same tendency with different pre-strains. And the stress increases when the pre-strain increases. No plastic deformation of the SMA sheet is found with the three pre-strains.

The SMA sheet thickness is one of the most important design parameters. To evaluate the influence of sheet thickness on the stress in the SMA sheet, three kinds of thickness of 0.15mm, 0.5mm and 1mm with actuator pre-strains of 4% are investigated. The results are show in Figure 6.

The results in Figure 6 shows the influence of the sheet thickness on stress in the SMA sheet. It can be seen that stress in the SMA sheet decreases drastically with increase of the thickness. And there is an interesting phenomenon that the degree of the stress step at location of Y=30mm tends to weaken when the sheet thickness increases. The thick sheet is hard to pull. Thus, the stress step tends to vanish when the thickness of the SMA sheet increases.
De-icing rate of the SMA de-icer with different pre-strains is investigated. Figure 7 depicts the de-icing rate of the SMA de-icer of different pre-strains and sheet thickness 0.15mm. Temperature of the shed ice is 254K.

![De-icing rate of different pre-strains](image1)

**Figure 7.** De-icing rate of different pre-strains

De-icing rate reaches 100% when the pre-strain is set as 4% and 6%. Stress output of the SMA de-icer is not enough to achieve the de-icing function with pre-strain of 3%. Considering the NiTi SMA material can achieve a maximum cycle life with the pre-strain of 4% [9], we adopted the pre-strain of 4% to fabricate the test model.

Influence of the sheet thickness on de-icing rate is considered. Figure 8 shows the de-icing rate results of different sheet thickness with pre-strains of 4%. From the results shown in Figure 8, we can conclude that the sheet thickness influences the de-icing rate greatly. The de-icing rate is 100% when the sheet thickness is 0.15mm. When the thickness increases to 0.5mm, de-icing rate drops to 61.1%. The SMA de-icer mostly loses efficacy when the sheet thickness exceeds 1mm. Thus, thin SMA sheet is recommended when designing the SMA de-icer.

Effect of adhesive ice temperature on de-icing rate is discussed. Figure 9 displays the de-icing rate results of different adhesive ice temperature with pre-strain of 4% and sheet thickness of 0.15mm.

![De-icing rate results of different adhesive ice temperature](image2)

**Figure 9.** De-icing rate results of different adhesive ice temperature
When temperature of the adhesive ice decreases, the de-icing rate maintains unchanged. This is because that elasticity modulus and shear modulus change little under various temperature of the adhesive ice. Thus, temperature of the adhesive ice impacts the de-icing rate little. Compared to the adhesive ice temperature, the pre-strain and the sheet thickness influence the de-icing rate much greater.

5. Conclusion
In this paper, we validated the de-icing performance of the SMA de-icer for non-rotating structure on aircraft and aero engine. The design of the SMA de-icer for non-rotating components is proposed. Characteristics of the SMA de-icer and factors influence on it were analysed numerically. The main conclusions of this study can be summarized as follows:

- The SMA de-icer can achieve de-icing objective well. A de-icing rate of 100% can be obtained.
- Pre-strain of 4% of the SMA sheet is recommended for de-icing.
- The SMA sheet thickness influences the performance of the de-icer greatly. A thinner SMA sheet is better for de-icing. And the thickness exceeding 1mm is unacceptable.

References
[1] Green S D 2006 A Study of U.S.Inflight Icing Accidents and Incidents,1978 to 2002 44th AIAA Aerospace Sciences Meeting and Exhibit (Reno, Nevada) pp 1 - 12.
[2] Lacey J J 1972 Turbine Engine Icing and Ice Detection ASME. 79818; ASME 1972 International Gas Turbine and Fluids Engineering Conference and Products Show, pp 1 - 4.
[3] Thomas S K, Cassoni R P and MacArthur C D 1996 Aircraft anti-icing and de-icing techniques and modeling J. Aircr. 33 841 - 54.
[4] Myose R Y, Horn W J, Hwang Y, Herrero J, Huynh C and Boudraa T 1999 Application of Shape Memory Alloys for Leading Edge Deicing General, Corporate and Regional Aviation Meeting and Exposition (GCRAM) pp 1 - 7.
[5] Möhle E, Haupt M C and Horst P 2013 Coupled Numerical Simulation and Experimental Validation of the Electroimpulse De-Icing Process J. Aircr. 50 96 - 102.
[6] Wang Y, Xu Y and Lei Y 2018 An effect assessment and prediction method of ultrasonic de-icing for composite wind turbine blades Renew. Energy 118 1015 - 23.
[7] Wang Y, Xu Y and Huang Q 2017 Progress on ultrasonic guided waves de-icing techniques in improving aviation energy efficiency Renew. Sustain. Energy Rev. 79 638 - 45.
[8] Meng X, Cai J, Tian Y, Han X and Zhang D 2016 Experimental Study of Anti-icing and Deicing on a Cylinder by DBD plasma actuation 47th AIAA Plasmadynamics and Lasers Conference pp 1 - 14.
[9] Gerardi J, Ingram R and Catarella R 1995 A shape memory alloy based de-icing system for aircraft 33rd Aerospace Sciences Meeting and Exhibit pp 1 - 8.
[10] Herrero J 2000 Implementation of a Composite Aircraft Deicer with a Shape Memory Alloy.
[11] Righi F, Sullivan D B, Hartl D J and Rogers J 2013 Shape Memory Alloy Rotor Blade Deicing 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference (Boston) pp 1 - 12.
[12] Cowin S C 2004 Anisotropic poroelasticity: Fabric tensor formulation Mech. Mater. 36 665 - 77.
[13] Labeas G N, Diamantakos I D and Sunaric M M 2006 Simulation of the Electroimpulse De-Icing Process of Aircraft Wings J. Aircr. 43 1876 - 85.