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Temperature sensors based on the temperature memory effect in shape memory alloys to check minor over-heating

C. Tang[a], T.X. Wang[a], W.M. Huang[a,*], L. Sun[b], X.Y. Gao[c]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore
[b] School of Civil Engineering, Shenyang Jianzhu University, Shenyang 110168, PR China
[c] School of Aeronautics Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

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ABSTRACT

In many occasions, such as in cold chain logistics, upon delivered to the customers, a cost-effective technique to check if any individual items (rather than a whole big box of them) have ever been slightly overheated is ideal for quality control. In this paper, we propose a possible method not only to check such an over-heating event in individual items, but also to reveal the highest temperature using NiTi shape memory alloy (SMA) via one single differential scanning calorimeter test. Three different types of temperature memory effect are investigated and the most applicable one, i.e., with good estimation of the actual over-heating temperature, is identified. The detailed implementation procedure for real practice is presented and the strategy to improve the accuracy is discussed. It is shown that in terms of checking the actual over heating temperature, a precision of within ±0.5 °C is achievable in both tested NiTi SMAs.

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1. Introduction

In many occasions, such as in a temperature-controlled supply chain (i.e., cold chain logistics), it is ideal to check if any individual items (instead of a whole container/box of them) have ever been slightly overheated and what the highest temperature was if over-heating did happen. Knowing if over-heating is only within a couple of °C might be critical to determine if the quality of an item, e.g., a piece of protein based medicine, is actually affected. In the current market, only a couple of commercial products (such as Thermax®) do not require electrical power for operating and are small enough, and thus suitable for checking the temperature of individual items upon delivered to the customers. However, in addition to high price and including harmful component (dye), they are still too bulky and non-flexible enough for small sized items.

Due to high actuation energy density [1], good bio-compatibility [2] and excellent resistance to corrosion [3], NiTi shape memory alloys (SMAs) have been utilized in many engineering applications, such as energy conversion, mechanical transmission, and biomedical device, etc. [1,4–8]. In general, heat is required to induce macroscopic shape change in pre-deformed NiTi SMAs for actuation [4,9]. On the other hand, since the underlying mechanism of shape memory effect (SME) in NiTi SMAs is due to the reversible martensitic transformation, which is temperature-dependent, theoretically NiTi SMAs have the potential to be used as temperature sensors as well. Previous attempts are largely based on macroscopic shape change (i.e., shape recovery) [10–13]. However, due to reliability problems, in particular due to strong influence of pre-straining on the transition temperatures [14], they are not seemingly commercially successful till today.

The temperature memory effect observed in many SMAs is another possible phenomenon to indicate the highest temperature in the previous thermal cycle(s). As reported in the literature [15,18], if the reverse martensitic transformation (from martensite to austenite) is interrupted in the middle of the transition, after cooling to achieve full martensite transformation, we can observe an additional trough in the differential scanning calorimetry (DSC) curve in the following heating process. Since the gap between the newly formed trough and the previous heating stop temperature is roughly a material dependent constant, this is called the temperature memory effect (TME). The release of elastic strain energy at the martensite–austenite interface during the martensitic transformation is suggested as the main cause of the TME [15]. In addition, it is possible to reveal even multiple heating stop temperatures with good accuracy, provided that these heating stop temperatures follow a descend order during thermal cycling. How-

* Corresponding author. Tel.: +65 67904859; fax: +65 67924062.
E-mail address: mwmhuang@ntu.edu.sg (W.M. Huang).

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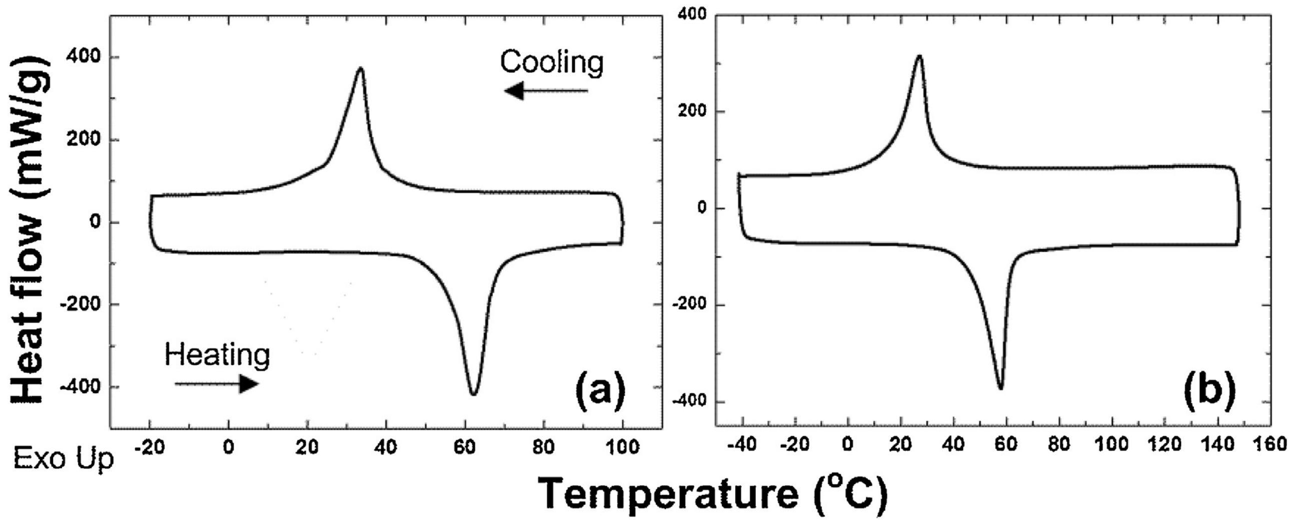

Fig. 1. Full range DSC result. (a) $Ni_{55.8}$ $Ti_{44.2}$ ribbon; (b) $Ni_{55.3}Ti_{44.7}$ wire.

ever, in the case of multiple thermal cycling, it is required that: (1) the heating stop temperatures must follow a descent order; and (2) the sample must be cooled to below the martensitic finish temperature (M_f) in each thermal cycle. These conditions can hardly be met in any temperature monitoring applications. In the course of this study, first we verify the TME of a SMA and confirm above mentioned limitations in the conventional approach. Then we explore two other possible ways to get rid of such limitations. In one of these two new ways, the lowest cooling temperature in each thermal cycle is between M_f and martensite start temperature (M_s), and in the other the lowest cooling temperature is above M_s.

Hereinafter, the testing procedure of the TME as reported in the past, in which the lowest temperature during cooling in each thermal cycle is always below M_f, is defined as c-TME; while the other two, one has the lowest cooling temperature between M_f and martensite start temperature (M_s), and the other has the lowest cooling temperature above M_s, are referred as m-TME I and m-TME II, respectively.

The outline of this paper is as following. Materials and experimental procedures are discussed in Section 2. Section 3 presents the experimental results with different testing conditions and parameters to reveal which approach may be utilized as the mechanism for temperature sensors to check over-heating temperature. Subsequently, the possible one for real engineering applications is further investigated in Section 4, together with the detailed procedure for implementation. Major conclusions are summarized in Section 5.

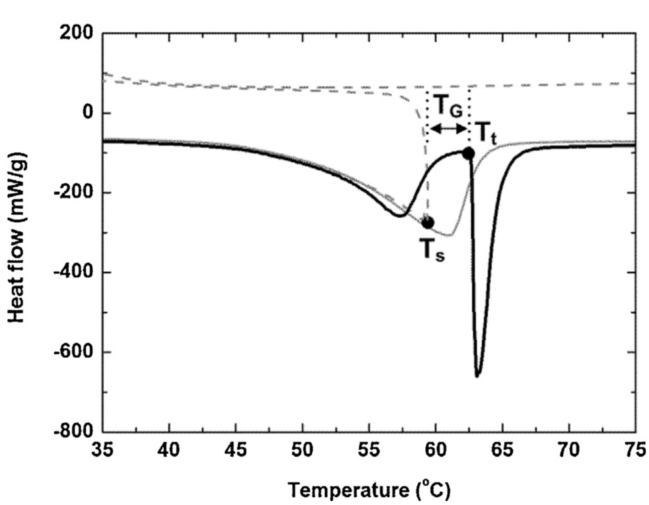

Fig. 2. Typical DSC curve of $Ni_{55.8}$ $Ti_{44.2}$ ribbon with T_s at 59.4 °C (single-stop, c-TME).

2. Materials and experimental procedures

Two types of NiTi SMAs were used in this study, one is $Ni_{55.8}$ $Ti_{44.2}$ ribbon with a cross-sectional area of $2 \times 0.2\,mm^2$, provided by Mide Technology Corporation, USA, and the other is 0.5 mm diameter $Ni_{55.3}Ti_{44.7}$ wire bought from SMA Inc., USA. As-received materials were annealed at 800 °C for one hour followed by quenching in iced water. After this treatment, excellent SME was observed in all of them. Small samples (less than 20 mg) were cut out of the ribbon or wire for DSC test using a TA Instrument DSC Q200A.

All DSC tests were conducted at a heating/cooling rate of 10 °C/min, so that the influence of heating/cooling rate is not considered in current study. It should be pointed out that the actual heating/cooling rate could have a very strong influence on the resultant DSC curve [16]. In the temperature monitoring applications, the SMA sample is expected to follow the temperature fluctuation of the individual items. Hence, if the mass of individual items is not too small, rapid heating/cooling could be avoided.

Fig. 1 presents the DSC results of both types of SMAs in a full thermal cycle. As we can see,

- In both types of SMAs, there is only one transition within the testing temperature range, i.e., one peak upon cooling (from austenite to martensite, which is the martensitic transformation) and one trough upon heating (from austenite to martensite, i.e., the reverse martensitic transformation);
- At 100 °C, both types of SMAs are austenite; and at 0 °C, both are almost pure martensite.

Based on the DSC results in Fig. 1, a series of DSC tests of c-TME, m-TME I and m-TME II were carried out on both types of SMAs. In each test, re-heating to 100 °C, which is well above the austenite finish temperature (A_f) of both SMAs and then cooling to 0 °C was conducted to ensure that the initial state of samples is almost full twinned martensite. In the following thermal cycle(s), heating was stopped at T_s, which is within the transition temperature range from martensite to austenite, followed by cooling to a prescribed temperature, namely T_c. Such a thermal cycling process might repeat a few times with predetermined T_s and T_c in each thermal cycle, before the sample was finally heated to 100 °C. Refer

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