Review on the temperature memory effect in shape memory alloys

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Shape memory alloys (SMAs) are well known for their unique shape memory effect (SME) and superelasticity (SE) behavior. The SME and SE have been extensively investigated in past decades due to their potential use in many applications, especially for smart materials. The unique effects of the SME and SE originate from martensitic transformation and its reverse transformation. Apart from the SME and SE, SMAs also exhibit a unique property of memorizing the point of interruption of martensite to parent phase transformation. If a reverse transformation of a SMA is arrested at a temperature between reverse transformation start temperature ($A_s$) and reverse transformation finish temperature ($A_f$), a kinetic stop will appear in the next complete transformation cycle. The kinetic stop temperature is a ‘memory’ of the previous arrested temperature. This unique phenomenon in SMAs is called temperature memory effect (TME). The TME can be wiped out by heating the SMAs to a temperature higher than $A_f$. TME can also occur in the R-phase transformation. However, the TME in the R-phase transformation is much weaker than that in the martensite to parent transformation. The decrease of elastic energy after incomplete cycle on heating procedure and the motion of domain walls have significant contributions to the TME. In this paper, the TME in the TiNi-based and Cu-based alloys including wires, slabs and films is characterized by electronic-resistance, elongation and DSC methods. The mechanism of the TME is discussed.

Keywords: temperature memory effect; shape memory alloys

1. Introduction

Shape memory alloys (SMAs) have attracted considerable interest as potential candidates for novel engineering and mechanical applications owing to their excellent functional properties, i.e. shape memory effect (SME) and superelasticity (SE) behavior. The unique effects of SME and SE originate from martensitic transformation and its reverse transformation. SMAs also exhibit a unique property of memorizing the point of interruption during transformation from martensite to parent phase. An incomplete thermal cycle upon heating of SMAs (arrested at a temperature $T_s$ between austenite transformation start and finish temperatures, $A_s$ and $A_f$) induced a kinetic stop in the next complete thermal cycle. The kinetic stop temperature is closely related to the previous arrested temperature. Therefore, this phenomenon is named the temperature memory effect (TME) [1].

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Figure 1. (a) Schematic illustration of the incomplete transformation cycling during the reverse martensitic transformation and subsequently complete cycling. (b) Typical DSC curves show the TME in shape memory alloys with R-phase transformation.

Figure 1a shows a schematic illustration of incomplete transformation cycling during the reverse martensitic transformation. Figure 1b shows a typical differential scanning calorimetry (DSC) curves showing the TME effect in the shape memory alloys. Previously this phenomenon was also named thermal arrest memory effect [2] or step-wise martensite to austenite reversible transformation [3,4]. The TME was firstly reported in thermally induced phase transformation in TiNi alloys [5], but then the TME has been reported in many other types of shape memory alloys [6–13]. The TME can be reinforced by the repetition of the partial heating up to $T_s$ (the so-called ‘hammer’ procedure) [14]. TME is also generally regarded as one-time phenomenon, i.e. the TME can be wiped out by heating the SMAs to a temperature higher than $A_f$. Liu et al. [15] have shown that an incomplete thermal cycling up to 80 times cannot retain the TME. However, a recent report showed that a repeatable TME can be introduced into a TiNi alloy by a pre-deformation larger than 12% [16]. The TME phenomenon has also been found in stress-induced transformations [4]. However, the TME in the stress-induced transformation cannot be erased by conducting complete mechanical–thermal cycles, but can be erased through an appropriate thermal treatment [4].

The TME can be potentially used to make the SMA act as a sensor to reveal the maximum temperature in the previous thermal or mechanical history. On the contrary, the TME means that the kinetics of the thermoelastic martensitic transformation can be dramatically modified by a previous partial cycle, which could be responsible for a lack of reproducibility during the service working conditions of SMAs devices and a loss of reliability in technological applications. Therefore, the TME has been attracting scientific and technological interest nowadays. In previous papers [8–12], we have characterized the TME in several types of SMAs with various kinds of forms, including TiNi-based and Cu-based alloys. In the present paper, we review all the factors that affect the TME in SMAs, and the mechanism of the TME has been explained.
2. TME in various SMAs

2.1. TME in TiNi-based SMAs belt and wire with a one-way shape memory effect

A one-way SME occurs when a SMA is in its martensitic state. The alloy can be bent or stretched and the deformed shape can be maintained. Upon heating above the reverse martensitic transformation temperature, the shape of the SMA changes to its original one. When the alloy cools down, it will remain in the high temperature shape, until deformed again. One-way SME is the basic characteristic of SMAs.

The DSC curve of Ti–43at.%Ni–7at.%Cu ribbons (which were annealed at 500°C for 3 h in an evacuated silica tube followed by air-cooling) with a global transformation cycle is shown in Figure 2a. Those of the TiNiCu ribbon with a single incomplete cycle upon heating at \( T_s = 58.6, 61.1 \) and 64.3°C are shown in Figure 2a. The kinetic stops can be clearly observed on the heat flow curves upon heating. Figure 2b shows the DSC results of the TiNiCu ribbon after performing three successive incomplete cycles upon heating at temperatures of 63.6, 61.3 and 58.3°C (with decreasing order). The three kinetic stops can be clearly observed corresponding to the previously arrested temperatures. Whereas we also performed three successive incomplete cycles upon heating at three arrested temperatures of \( T_s = 58.3, 61.3 \) and 63.3°C but with an increasing order. Only one kinetic stop can be observed, and the maximum temperature of \( T_s = 63.3°C \) is memorized. The phenomenon shows that only the highest temperature of the three successive temperatures (with increasing order) is memorized. It implies that a further heating to a temperature exceeding the previous stop temperature can wipe out the TME caused by the previous stop temperature. The TME is a reversible process. From Figure 2b, it can be noticed that the transformation kinetics of the global transformation is completely recovered in the following complete cycle.

The heat flow detected on heating and cooling for a Ti–49.8at.%Ni wire with diameter of 0.55 mm (which was electrothermally annealed with 9.3 A/mm² and 12.2 A/mm² direct electrical current for 1 h) is given in Figures 3a and 3b. The sample has been preformed for a global transformation or a single incomplete cycle on heating at \( T_s = 67.4, 68.9 \) and 70.4°C and \( T_s = 74.4, 77.3 \) and 79.3°C, respectively. The TME is clearly evident on the

![Figure 2](image-url)

Figure 2. (a) DSC results of a TiNiCu ribbon and the TME of same sample with single incomplete cycle on heating at 58.6, 61.1 and 64.3°C. (b) DSC results showing the TME of TiNiCu ribbon with single stop at \( T_s = 63.6, 61.3 \) and 58.3°C with decreasing order, \( T_s = 58.3, 61.3 \) and 63.3°C with increasing order and subsequent global transformation.
2.2. TME in TiNi-based SMAs with two-way shape memory effect

The two-way SME in SMAs involves reversible spontaneous shape changes during cooling and heating. This is a consequence of reversible phase transformations without any external stresses. The two-way SME is not a coherent property of SMAs and usually is obtained after a thermo-mechanical treatment, often called training. There are several training methods for obtaining a two-way SME. These methods have the common feature of introducing irreversible defects into the parent phase, such as dislocations [19], stabilized stress-induced martensite phases [20] and precipitates [21]. When the specimen transforms into martensite, the growth of the martensite will be controlled by the internal stress fields of the irreversible defects, so the shape change of the specimen also occurs at a low temperature. We have designed two methods to obtain two types of coil TiNiCu springs with the two-way SME [22,23]. The first type is the extension spring, which can extend upon heating and contract upon cooling, and the second type is the contraction spring, which can contract upon heating and extend upon cooling.

Figure 4a shows the contraction rate–temperature curve of the TiNiCu spring with a global transformation cycle. The details of the processing of the spring can be found in [24]. The contraction rate–temperature curves of TiNiCu springs with a single incomplete cycle upon heating at $T_s = 63$ and $66^\circ$C, respectively, are shown in Figures 4b and 4c. The plateaus are clearly observed on the contraction rate-temperature curves upon heating. Figure 4a’ shows the DSC curve of TiNiCu contraction spring with a global transformation cycle. Figures 4b’ and 4c’ show the DSC results of the TiNiCu spring after heating.
performed an incomplete cycle at a temperature between \( A_s \) and \( A_f \) upon heating. The kinetic stop temperatures are identical to those in Figures 4b and 4c.

Figure 5a shows the results of the TiNiCu springs after performing two successive incomplete cycles with a decreasing order upon heating at temperatures of 68 and 63\( ^\circ \)C, and two plateaus are observed corresponding to the two arrested temperatures. Figure 5b shows the results of the TiNiCu springs after performing two successive incomplete cycles upon heating at temperatures of 63 and 68\( ^\circ \)C with an increasing order. Only one plateau can be observed from Figure 5b, and only the maximum temperature of \( T_s = 68^\circ \)C is memorized. The phenomenon shows that only the highest temperature of the two temperatures (with increasing order) is memorized. This implies that a further heating to a temperature exceeding the previous stop temperature can wipe out the TME caused by the previous stop temperature. If a number \( N \) of incomplete cycles on heating with different arrested temperatures is performed in a decreasing order, \( N \) plateaus can be found. The TME is a reversible process. From Figure 5c it can be seen that the plateaus of the global transformation (Figures 5a and 5b) are completely eliminated in the following complete cycle. The above results are confirmed by the DSC results shown in Figures 5a’–5c’.

Figure 6a shows the results of the TiNi [24] spring after performing 1, 60 and 120 incomplete cycles upon heating at the temperature \( T_s = 65^\circ \)C. Figure 6b also shows the contraction rate–temperature curves of the TiNiCu spring by performing 1, 60 and 120 incomplete cycles upon heating at the temperature of 65\( ^\circ \)C. With increasing number of incomplete cycles, the plateau is widened toward to high temperature, as shown in Figures 6a and 6b, indicating that the TME is enhanced by multiple incomplete transformations.

2.3. TME in TiNi-based SMA films

SMA thin films have been recognized as a promising material for applications in micro-electro-mechanical-systems, due to their shape memory effect, large energy density, pseudoelasticity, biocompatibility and high damping capacity [25]. SMA films can also
Figure 5. Contraction rate–temperature curve of TiNiCu spring with two incomplete cycle at $T_s = 68$ and $63\,^\circ C$ with decreasing order (a), $T_s = 63$ and $68\,^\circ C$ with increasing order (b) and subsequent global transformation (c); DSC results of TiNiCu spring with two stops at $T_s = 68$ and $63\,^\circ C$ with decreasing order (a'), $T_s = 63$ and $68\,^\circ C$ with increasing order (b') and DSC result of subsequent global transformation (c').

Figure 6. The temperature memory effect of the 1st, 60th and 120th working cycles at $T_s=65\,^\circ C$ in (a) TiNi spring and (b) TiNiCu spring.

provide a higher frequency response and longer life time at the microscale compared with bulk SMA. Ti–41at.%Ni–9at.%Cu (TiNiCu9) and Ti–46at.%Ni–4at.%Cu (TiNiCu4) thin films were prepared by co-sputtering of a TiNi target and a Cu target on (100) silicon wafers using a magnetron sputter, Coaxial MSS3A, England [26]. The substrate temperature was 450\,^\circ C and substrate holder was rotated during deposition to achieve the uniform deposition. The base pressure of main chamber was $1 \times 10^{-7}\text{Torr}$. The argon pressure was 1.0 mTorr during deposition and the substrate-to-target distance was 100 mm. TiNiCu9 films peeled off from the Si substrate and TiNiCu4 film on the Si substrate were used for the TME measurements.
Figure 7. (a) DSC results of a TiNiCu4 thin film and the TME of same sample with single incomplete cycle on heating at 75.2, 76.7, 78.2 °C, and three single stops at $T_s = 78.2$, 76.7 and 75.2 °C with decreasing order. (b) DSC results of a TiNiCu9 thin film and the TME of same sample with single incomplete cycle on heating at 49.6, 51, 52.1 °C, and three single stops at $T_s = 50.8$, 50 and 48.7 °C with decreasing order.

Figure 7 shows the DSC results of the TiNiCu4 film attached on a Si substrate. Upon heating and cooling, there is only one peak observed, corresponding to the transformation between austenite and martensite. Figure 7 also shows the TME of the TiNiCu4 thin film with one single incomplete cycle upon heating at arrested temperatures of 75.2, 76.7 and 78.2 °C. Clearly one kinetic stop temperature, corresponding to the arrested temperatures can be observed for each of the DSC curves. Three kinetic stop temperatures can be observed in the curves after performing three successive stops at $T_s = 78.2$, 76.7 and 75.2 °C with a decreasing order. For all the above results, the kinetic stop temperature is slightly higher than the arrested temperature.

Figure 7b shows the DSC results of the free-standing TiNiCu9 films (peeled from the Si substrate). Upon heating and cooling, there is only one peak observed, corresponding to transformation between austenite and martensite. Figure 7b also shows the TME of the TiNiCu9 thin film in one single incomplete cycle upon heating, stopping at arrested temperatures of 49.6, 51 and 52.1 °C. Clearly only one kinetic stop temperature can be observed in each test. Three kinetic stop temperatures can be clearly observed in the curve after performing with three successive stops at $T_s$ of 50.8, 50 and 48.7 °C with a decreasing order. Comparing the results from Figures 7a and 7b, it can be concluded that the substrate has no effect on the TME.

2.4. **TME in Cu-based SMAs**

Cu-based SMAs have attracted much attention for their good shape memory capacity and a narrow temperature region of transformation, and they are easier to fabricate and less costly than TiNi alloys. Cu–Zn-based SMAs have actually been used in industry, and Cu–Al-based SMAs have shown their promise for future applications. In this section, we compared
the TME in a polycrystalline Cu–21.5wt%Zn–5.85wt%Al SMA with a thickness of 0.80 mm and a single crystal Cu–14wt%Al–4.2wt%Ni with a thickness of 1.0 mm. The CuZnAl alloys were annealed at 760°C for 7 min and quenched in the water at 100°C. The CuAlNi alloys were annealed at 810°C for 20 min and quenched in oil at 120°C.

The complete and incomplete transformation behaviors of the CuZnAl polycrystals are shown in Figure 8a. In order to make the TME more evident, the derivatives of the heat flows upon heating are shown in Figure 8b. Those of the CuZnAl sample with a single incomplete cycle upon heating at $T_s = 73.9$ and 76.2°C, respectively, are shown in curves (i) and (ii), and the kinetic stops are clearly observed on the heat flow curves upon heating. Curve (iii) shows the DSC results of the CuZnAl after performing two successive incomplete cycles upon heating at temperatures of $T_s = 73.8$ and 76.3°C with a sequential increasing order. Only one kinetic stop can be clearly seen corresponding to the maximum temperature of $T_s = 76.3$°C. Two kinetic stops can be clearly observed after performing two successive incomplete cycles upon heating at the arrested temperatures of $T_s = 76.3$ and 73.8°C with a sequential decreasing order, as shown in curve (iv). The phenomenon shows that only the higher temperature of the two successive temperatures is memorized, which implies that a further heating to a temperature exceeding the previous stop temperature can wipe out the TME caused by the previous stop temperature.

![Diagram](image)

Figure 8. TME in CuZnAl polycrystals with single incomplete cycle on heating at $T_s = 73.9$, 76.2°C and two successive arrested temperatures of $T_s = 76.3$, and 73.8°C with sequential ordering or $T_s = 73.8$, and 76.3°C with sequential ordering. (a) Heatflow vs. temperature and (b) derivation of heat flow vs. temperature.
Figure 9. TME in CuAlNi single crystals with single incomplete cycle on heating at $T_s = 57.0$, 58.9°C and three successive arrested temperatures of $T_s = 59.4$, 58.0 and 56.5°C with sequential ordering. (a) Heat flow vs. temperature and (b) derivation of heat flow vs. temperature.

The complete and incomplete transformation behaviors of the CuAlNi single crystals are shown in Figure 9a, and the corresponding derivatives of the heat flows upon heating are shown in Figure 9b. Single kinetic stops are also clearly observed on the heat flow curves upon heating after performing a single incomplete cycle upon heating at $T_s = 57.0$ and 58.9°C, respectively. Three kinetic stops can be clearly observed after performing three successive incomplete cycles upon heating at three arrested temperatures of $T_s = 59.4$, 58.0 and 56.5°C with a sequential decreasing order.

The above results show that the TME appears in both the single crystals and polycrystals after performing the incomplete reverse M→P transformation. However, the TME in the single crystals is less evident than that in polycrystals, as already shown in previous literature results on the CuZnAl single crystals [27]. This result clearly indicates that the grain boundaries have contribution to the TME.

2.5. TME in R-phase transformation

In near-equiatomic TiNi alloys, the martensitic transformation can occur either as the direct B2→B19′ or through the intermediate R phase B2→R→B19′ depending on the thermal or thermomechanical treatments [28]. R phase is another potential martensite candidate for SME, especially in the presence of a finely dispersed Ti$_3$Ni$_4$ precipitation in a B2 matrix [29]. The R-phase transformation is martensitic and thermoelastic, and it also shows SME
and SE [30–32]. The R-phase transformation in the TiNi alloy is particularly important, since it exhibits very small temperature hysteresis and has been utilized in most of the practical applications of the TiNiSMAs [22].

Figure 10 shows the global transformation behavior of four TiNi samples with different heat treatments. The composition and heat treatments are listed as follows:

Sample 1: A binary Ni-rich TiNi SMA with a composition of Ti–50.6at.%Ni was solution annealed at 800°C for 20 min and then quenched to 0°C. After the solution treatment the sample was annealed at 450°C for 1 h.
Sample 2: A binary Ni-rich TiNi SMA with a composition of Ti–50.6at.%Ni was annealed at 450°C for 1 h.
Sample 3: A Ti–49.8at.%Ni wire with a diameter of 0.55 mm was annealed at 400°C for 1 h.
Sample 4: A Ti–49.8at.%Ni wire with a diameter of 0.55 mm was electrothermally annealed with 9.3 A/mm² direct electrical current for 1 h.

The global transformation result shows that upon cooling, a two-step transformation among austenite, R phase and martensite can be observed. Upon heating, only one step transformation between martensite and austenite can be detected for the samples of 2, 3 and 4. A multi-step martensitic transformation appears in the sample 1.

Figure 11 shows DSC results of the transformation between R phase and parent phase, which can be used to check the TME. For sample 1, we cannot see any interruptions or distortions of the DSC curves after performing one repetition incomplete transformation.

Figure 10. Global transformation behaviors of four TiNi samples, which were tested with scanning rate of 10°C/min.
Figure 11. DSC results showing the TME in the R-phase transformation in four TiNi samples which were tested with scanning rate of 2\degree C/min. The \( T_s \) are (a) 32.3, (b) 41.6, (c) 52.3 and (d) 54.8\degree C.

from Figure 11a. A small shoulder appears at about 32.7\degree C after performing five repetitions, and the shoulder becomes clearly defined after performing 10 repetitions. The TME can be easily found in sample 2. A shoulder appears at about 41.89\degree C after performing one repetition and separates into a distinct peak after performing five repetitions, as shown in Figure 11b. The TME can also be observed in sample 3, which is shown in Figure 11c. However, the TME cannot be observed after performing one repetition and only a shoulder appear after performing 10 repetitions, see Figure 11d.

2.6. TME in other shape memory alloys
Ferromagnetic shape memory alloys (FSMAs) have in recent years become an important part of sensor and actuator materials due to their large magnetic-field-induced strain and SME [33,34], including Fe–Pd [35], Ni–Mn–Al [36], Co–Ni–Al [37], Ni–Fe–Ga [38,39], etc. Among these magnetic SMAs, the NiMnGa alloys are the most well-studied systems for their large magnetic-field-induced strain. Dilatometry is a method that measures all deformation occurring in a material, which also can be used to detect the transformation. Dilatometry has been used to study the TME in polycrystalline ingots of both Ni_{53.3}Mg_{27.1}Ga_{19.3} and Ni_{54.2}Mn_{29.4}Ga_{16.4} alloys, which were prepared by arc melting in an argon atmosphere.
2.7. Incomplete transformation upon cooling

It was reported that there was no TME for a partial reverse B2→B19′ transformation. Figures 12a and 12b show the DSC results of the TiNiCu4 and TiNiCu9 films after performing an incomplete cycle at a temperature between $M_s$ and $M_f$ upon cooling. For all the testing results, there is no evidence of kinetic interruption for the next complete P→M transformation. However the effect of incomplete transformation upon cooling can induce multistage reverse transformation in a sample showing R-phase transformation.

Figure 13a shows the DSC results of a Ti–49.8at.%Ni wire annealed at 400°C for 1 h. The global transformation result shows that, upon cooling, a two-step transformation among austenite, R phase and martensite can be observed, whereas, upon heating, only one-step transformation from martensite to austenite can be detected. With a ‘turn-back’ temperature lower than $R_s$ but higher than $M_s$, the heat flow curve detected upon following heating shows one endothermic peak. The peak shifts to the lower temperature side than that of the martensite to parent transformation in a global transformation. On decreasing the ‘turn-back’ temperature $T_s$ to a temperature between $M_s$ and $M_f$, two endothermic peaks can be observed upon the following heating. The second peak lies in the temperature range between $A_s$ and $A_f$.

Figure 13b shows the DSC results of the Ti–49.8at.%Ni wire annealed at 450°C for 1 h. A two-step transformation process among austenite, R phase and martensite takes place upon cooling, and a one-step reverse transformation occurs upon heating for the global transformation. However, the B2→R-phase and R-phase→B19′ transformation peaks overlap; thus the R-phase→B19′ transformation peak appears as a shoulder on that of B2→R-phase transformation. The splitting of the reverse phase transformation peaks (i.e. two endothermic peaks) can also be observed after performing an incomplete transformation upon cooling.

Figure 13c shows the DSC results of the Ti–49.8at.%Ni wire annealed at 550°C for 1 h. The global transformation behavior shows that the R phase disappears and austenite transforms into martensite directly. After performing an incomplete transformation upon cooling, there is only one peak appeared upon heating, without splitting of peaks occurred.

Figure 13d shows the DSC results of the free-standing Ti–49.8at.%Ni thin films. The global transformation result shows that upon heating, a one-stage transformation is
observed, i.e. from martensite (B19') to parent phase (B2). Upon cooling, there is a two-step transformation among B2, R and B19' phases. This transformation sequence has also been confirmed by in situ X-ray diffraction (XRD) at different temperatures [26]. The similar peak-splitting effect in the heating after an incomplete transformation is observed.

Figure 13. DSC results of a Ti–49.8at.%Ni wire annealed at (a) 400, (b) 450 and (c) 550°C for 1 h after performing an incomplete transformation upon cooling. (d) DSC results of a Ti–49.8at.%Ni thin film.
When the ‘turn-back’ temperature is arrested at a value between $R_f$ and $M_s$, the heat flow detected upon following heating only shows one endothermic peak. On decreasing the ‘turn-back’ temperature $T_s$ to a value between $M_s$ and $M_f$, two endothermic peaks can be observed upon the following heating.

For the TiNi wire annealed at 400°C, on decreasing the ‘turn-back’ temperature $T_s$, the transformation heat of the first peak increases to a maximum value, then decreases afterwards, whereas that of the second peak increases continuously. The first peak corresponds to the R-phase→B2 transformation and the second peak the B19′→B2 transformation. When the ‘turn-back’ temperature is arrested at a value lower than $R_s$ but higher than $R_f$, only part of the parent phase transforms into the R phase (we call it R1), with the rest of the parent phase remaining. During the following heat process only the transformation of R1 to austenite contributes to the latent heat. With a decrease of $T_s$, more R phase (R1) forms, leading to an increase in the latent heat of the first peak. When the ‘turn-back’ temperature is arrested at a value lower than $M_s$ but higher than $M_f$, the parent phase transforms into R phase completely, but only part of the R phase transforms into the martensite (we call it M1), with the rest of the R phase remaining. During the following heating process, the remaining R phase and martensite will transform into the parent phase, contributing to the latent heat of the first peak and the second peak, respectively. With the decrease of $T_s$, more M1 forms, leading to the decrease of the latent heat of the first peak and increase of the second peak. For the sample annealed at 500°C, there is no R-phase transformation occurring. When the austenite to martensite transformation is arrested at a certain temperature between $M_s$ and $M_f$, only part of the parent phase transforms into the martensite, with the rest of the parent phase remaining. Therefore, with a decrease of $T_s$, more martensite forms, which leads to an increase of the latent heat of transformation. The multistage transformation of the reverse transformation can be attributed to the differences of transformations between R phase to parent phase and martensite to parent phase. This may be caused by the less lattice movement and small transformation strain of R-phase transformation compared to those from martensitic transformation [40], thus less driving force is required to finish the R phase to parent phase transformation compared to that of the martensite to parent phase transformation. Therefore, the R-phase→B2 transformation could occur at a lower temperature, whereas the martensite→B2 transformation could happen at a higher temperature.

3. Discussion

From above results, following conclusions can be obtained:

(1) TME is a common phenomenon in SMAs, caused by a partial martensite to parent phase (M→P) transformation, which can occur in various types of the SMAs, including TiNi-based, Cu-based and NiMnGa alloys.

(2) TME can occur in SMAs with various forms, including belt, wires, films, SMAs with one-way SME and two-way SME.

(3) TME can occur in the SMAs with single and multiple staged martensitic transformations.

(4) TME can occur in single- and polycrystalline SMAs, however, TME in single crystals is less evident than in polycrystals.

(5) TME can be observed in SMAs though all types of method, such as calorimetric measurements, electronic resistance method, dilatometry and wafer curvature method.
(6) TME can be enhanced by multiple incomplete transformations.

(7) \( N \) points of temperatures could be memorized if \( N \) numbers of incomplete cycles on heating are performed with different arrested temperatures in a decreasing order, while only the high temperature can be memorized in an increasing order.

(8) TME can occur due to partial R phase to parent phase transformation and martensite to parent phase transformation. However, the former is much weaker than the later.

(9) In most cases, TME can be wiped out by heating the SMAs to a temperature higher than \( A_f \). However, a repeatable TME can be introduced into a TiNi alloy by large deformation (>12%).

(10) TME cannot occur for a partial parent to martensite (or R-phase) transformation; however the effect of incomplete transformation upon cooling can induce multistage reverse transformation in a sample showing R-phase transformation.

Some attempts to describe these phenomena have been published in recent years [16,41–44], which attribute the observed behavior to different mechanisms such as changes in the crystal elastic energy, dislocation structure, motion of domains, interfaces interaction, etc.

When the transformation from the martensite to austenite transformation is stopped at a certain temperature \( T_s \), only part of the martensite transforms into the parent phase, while the rest of the martensite remains, called M1. When the temperature decreases below \( M_f \), the parent phase transforms back into martensite that is defined as M2. The M2 and M1 transform into the parent phase sequentially, with a kinetic stop between them for the next heating stage. It has been suggested that the TME is associated with elastic strain energy, which serves as the driving force during the reverse transformation [45]. Madangopal et al. [2] proposed that M2 could store more elastic strain energy than M1 in a global transformation; therefore the reverse transformation of M2 could be somehow pre-positioned. Airoldi et al. [4] explained the TME in terms of the lack of elastic strain energy in M2. Therefore, a higher temperature is necessary to finish the transformation of M2 and to start the transformation of M1. The results obtained by Zheng et al. [16] show that the formation of M2 is due to the nucleation and growth of martensite nuclei in the parent phase, but not the growth of the existing M1 martensite. Otherwise, M2 should have the same oriented structures as M1, if the growth of M2 is based on M1. Therefore, M1 and M2 transform into parent phase at different temperatures for the next heating process.

Martensitic transformation in shape memory alloys occurs between austenite (A, a crystallographic more-ordered parent phase) and martensite (M, a crystallographic less-ordered product phase). The free energy of the nucleation of a plate of martensite is given as [46]:

\[
\Delta G_{\text{Nucl}} = \Delta G_{\text{Chem}} + \Delta G_{\text{Non-Chem}} + \Delta G_{\text{Interface}}.
\] (1)

In the case of ordered shape memory alloys, a reduction in \( \Delta G_{\text{Nucl}} \) can be achieved by the minimization of \( \Delta G_{\text{Non-Chem}} \) through the formation of self-accommodating variants. The elastic strain energy will be stored in the thermoelastic martensite variants. During the transformation from B2 phase to martensite phase, the interphase boundaries between the martensites and the parent phase are coherent phase boundaries, called the habit planes, and the coherent energy resulting from the lattice distortions at the coherent interfaces has a prominent effect on the transformation characteristics [47]. When the martensite to
austenite transformation is stopped at a certain temperature $T_s$, only part of the martensite transforms into the parent phase. There exists coherent stress between the two phases. When the temperature is decreased below $M_f$, the parent phase transforms back into martensite. Using *in situ* transmission electron microscopy, Bataillard et al. [48] observed that B19′ martensite nucleates from stress regions and then grows into the matrix (stress free region). New orientated martensite M2 will form which are favored by these coherent stresses. Figure 14 schematically shows one possible transformation process of TME in SMAs. Upon heating, part of the martensite transforms to parent phase with M1 martensite phase remains. M2 martensite phase forms upon cooling, and domain boundaries appear between the M1 and M2 martensite phase. The newly formed M2 martensite at the M1–M2 interface will accommodate itself to decrease the elastic strain energy level. This leads to release of the stored elastic strain energy in M1 at the M1–M2 interface. As the first formed martensite plate is the last to revert to the parent phase and vice versa [49], and much more work is needed to overcome the domain boundary motion. Therefore, the release of the elastic strain energy and more work to overcome the motion of domain boundaries lead to the shift of the transformation of M1 to a higher temperature, and a kinetic stop appears upon heating. Evolution of surface morphology of a single crystal CuAlNi SMA at the interrupted temperature have confirmed the formation of possible new martensite [44], but this needs to be verified by other methods, such as *in situ* TEM.

Dislocations and grain boundaries also contribute to the TME. There exist much grain boundaries in polycrystals, and the work needed to overcome the motion of domain boundaries is larger than those in the single crystals. Therefore, the TME in polycrystals is more evident than that in the single crystals. Dislocations act as kinetic barriers to martensitic transformation, and leave a kinetic stop on the following global transformation. Obviously, large deformation induces a large amount of dislocations into SMAs, which makes the separation between M1 and M2 much clearer, thus can make the TME more repeatable [16].

4. Conclusion and future directions
The temperature memory effect (TME) induced by an incomplete cycling in various types of shape memory alloys (SMAs) has been reviewed. The results show that TME is a...
common phenomenon in SMAs, which is induced by a partial reverse martensitic transformation. On the contrary, if a partial martensitic transformation is performed by an incomplete cycle during cooling, the next complete martensitic transformation does not show any evidence of the TME. The effect of this type of incomplete transformation upon cooling can induce multistage reverse transformation in a sample showing R phase transformation. Elastic strain energy, dislocations and grain boundaries play an important role in the TME. It is necessary to develop a phenomenological model to reproduce all of the TME related phenomena observed in experiments.

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