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Wide Range Temperature Memory Effect of an In Situ NiTi Alloys Composite

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Incomplete martensitic transformation characteristics of NiTi shape memory alloys after cold deformation were studied. By designing the shape of the original surface curve, macroscopic domains with different dislocation density were introduced into the NiTi alloys and materials possessing the characteristics of composites were obtained. Due to the interactions between the dislocation texture and martensite variants, the reverse transformation temperatures were found to expand over a large temperature window, which gives temperature memory effect a higher potential for application.

Keywords cold deformation, incomplete martensitic transformation, NiTi alloy, shape memory alloy, wide range temperature memory effect

1. Introduction

Shape memory alloys (SMAs) are known having the ability of remembering their shape in the parent phase. This shape memory effect has been extensively studied in the past decades (Ref 1, 2). Besides the shape memory effect, some researches have also shown that SMAs have the ability of memorizing their thermal history (Ref 3-6). That is, if the reverse transformation of a SMA is interrupted, a kinetic stop will appear in the next complete reverse transformation. The kinetic stop temperature always falls in a position a little higher than the previous interruption temperature, so it is reasonable to call this kinetic stop temperature a "memory" of the previous interruption temperature.

This temperature memory effect (TME), however, has not received intensive attention. One main reason is that TME was once believed willing to appear just in a temperature range between A_s and A_f (which are the reverse transformation starting temperature and finishing temperature, respectively). Usually the temperature interval between A_s and A_f is less than 30 K, which is too narrow for application.

However, our previous investigations have shown that a prestrained NiTi alloy embedded in a composite has a much wider transformation temperature range than an alloy in a free state, due to the presence of the recovery stress. Therefore, a moderate heating of the composite results in an in-complete transformation cycling of the embedded NiTi alloy wire. But, the interfacial bond cannot postpone the finishing temperature of prestrained wire in a composite without limit, due to the interface fails or plastic deforms. This upper temperature limit restricted the application of TME.

In the present work, our aim is to study the TME of an in situ composite with macroscopic heterogeneous structure formed by cold rolling, and we show that the temperature memory effect can be expanded to be operational in a wider temperature range by cold roll a curved surface NiTi alloy.

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2. Experimental Procedure

A $Ti_{50}Ni_{50}$ alloy rod was obtained from the Generous Research Institute for Non-ferrous Metals, China. The rod was vacuum annealed at 873 K for 1 h, and then spark cut into sheets with sinusoidal surface and a maximum thickness of 2 mm. Two samples were designed with amplitudes of the surface sinusoidal wave of 0.1 and 0.2 mm, respectively. By deformation to a thickness of 1.6 and 1.2 mm, the two samples had a nominal minimum deformation of 0%, and maximum deformation levels of 20% (named Wave-20%) and 40% (named Wave-40%), respectively. Figure 1 schematically shows the macroscopic heterogeneous structure formed by cold rolling. An SMA sheet with wavelike surface has different thickness in different parts. Therefore, a cold rolling causes different deformation levels in different parts. The right part of Fig. 1 shows the internal structure of the sheet after cold rolling, where "a" represents the region with relatively large deformation level (and therefore with weak shape recovery ability), and "b" represents the region with relatively small deformation level (and therefore with strong shape recovery ability). One can see that the heterogeneous in a SMA is magnified in such a way that macroscopic distinct domains are aligned regularly, and then the SMA has a structure similar to those of composites. The best advantage of the composite shown in Fig. 1 over conventional SMA composites is that the in situ composite has a graded interface between different domains, whereas conventional SMA composites has a distinct interface between different phases and are more susceptible to interfacial debonding than any other composites (Ref 7, 8). Samples for differential scanning calorimetry (DSC) and thermal expansion measurement were cut using a low speed diamond saw. The DSC and the thermal expansion measurements were conducted using a Netzsch DSC 2004 Phoenix and a WRP-1 computerized dilatometer.

3. Results and Discussion

Figure 2 shows the temperature memory effect of the NiTi wire without any deformation. The global reverse transformation curve is reproducible by complete thermal cycling between M_f and A_f. If the global reverse transformation is interrupted at a certain temperature T_s, for example, at 337.1 K, as shown in Fig. 2, only part of the martensite transforms into the parent phase, with the rest of the martensite remaining. We call the remaining martensite M1. Decreasing the temperature below M transforms the parent phase back into martensite. This newly formed martensite is called M2. One can see in Fig. 2 that, during heating, M2 and M1 transform into the parent phase sequentially, with a kinetic stop between them. It is known that the kinetic stop temperature is always about 3 K higher than T_s. Therefore, without knowing the T_s temperature, one can still find it, with a maximum error of 3 K, by examining this kinetic stop.

Figure 3 shows the temperature memory effect of the Sine-20% sample. The heating process was, respectively, interrupted at 426 K three times, a temperature much higher than the reverse transformation temperature (A_f) of the alloy. In the second heating, an endothermic peak appeared right at the position of T_s, indicating that these Wave-type samples had "remembered" the arrested temperature. It is worth to note that the transformation temperatures are significantly enlarged by the severe cold deformation, as can be seen in Fig. 3. By using the method shown in Fig. 1, one can have the advantages of both a much-pronounced endothermic peak on the DSC curve, and a wide transformation temperature range. We can regard this kinetic stop as a "memory" of the previous arrest temperature (Ref 9). Our previous research (Ref 7, 8) has shown that by embedding a prestrained SMA wire into composites, one can have a much wider transformation temperature window and therefore the ability to remember the arrested temperature in the previous heating process over a wide temperature window. However, the interface of a SMA composite is usually very vulnerable to thermal shock. For samples prepared by the method shown in Fig. 1, no such a vulnerable interface is presented. Therefore, samples prepared by the method shown in Fig. 1 can demonstrate the temperature memory effect over a much wider temperature range than an ordinary SMA composite.

Figure 4 shows the expansion curves of the samples Sine-20% in the thermal cycle, which can be regarded as a proof of the above description. One can also see from Fig. 4 that by an intended design, Sine-type samples can overlap a desirable (also adjustable) strong negative strain over a moderate negative strain, indicating the existence of the ongoing reverse transformation. Due to the partial reverse transformation, thermal expansion curves of the samples Sine-20% show a strain plat (cd) in the forth thermal cycle.

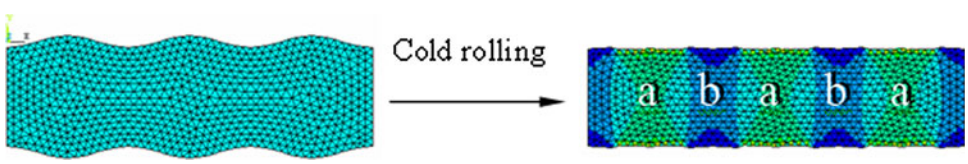

Fig. 1 Preparation of in situ SMA composite by cold rolling. Left: before cold rolling(sine-wave), right: after cold rolling, where "a" refers to the domain with relatively large deformation level, and "b" refers to the domain with relatively small deformation level

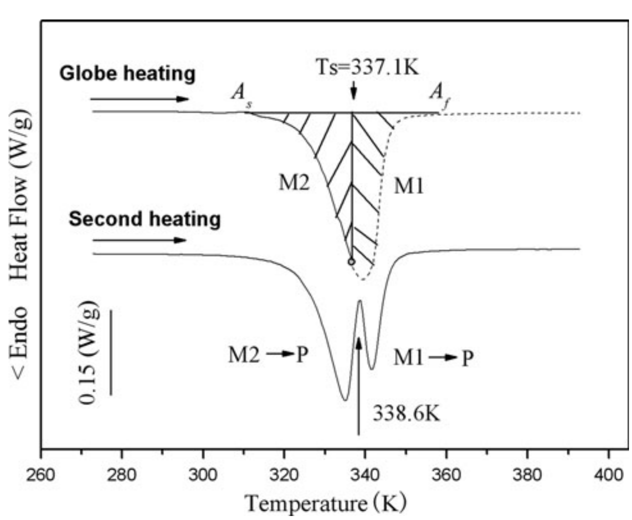

Fig. 2 DSC curves of all samples after different levels of deformation. DSC results showing the temperature memory effect of an undeformed NiTi wire

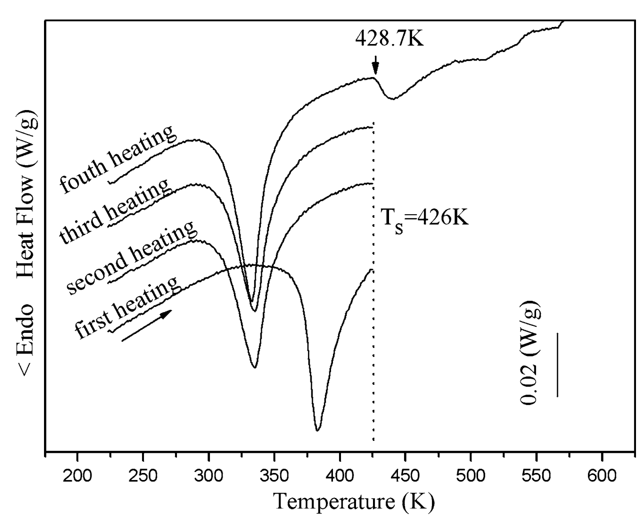

Fig. 3 The temperature memory effect demonstrated by the partial reverse transformation of the sample Sine-20%

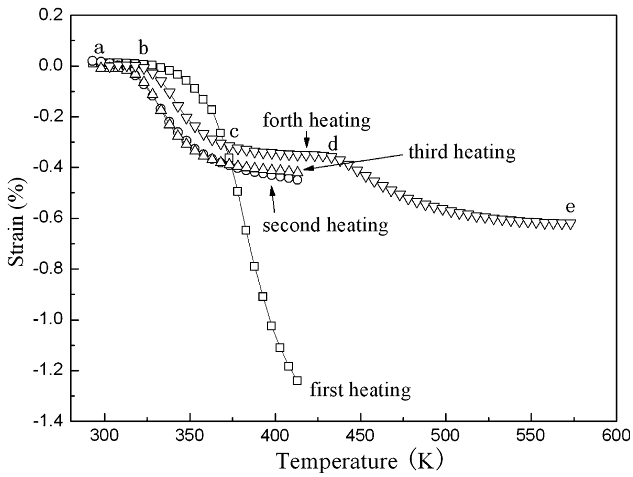

Fig. 4 Thermal expansion curves of the Sine-20% samples in the third heating cycle

It is well known that the constrained heating of a prestrained SMA will result in a gradual buildup of recovery stress, and therefore a significantly enlarged reverse transformation temperature range, according to the Clausius-Clapeyron equation. Obviously, the recovery stress plays an important role in NiTi composites. The heavily cold rolled NiTi alloy gained a great spatial inhomogeneity in strains, which resulted in a wild reverse transformation temperature range, whose temperature is different from one place to the other. During the partial reverse transformation, the martensite to austenite transformation is stopped at a certain temperature between A_s and A_f, and only part of the martensite transform into the parent phase, with the rest of the martensite remaining. Here the remaining martensite is called M1. With further decreasing the temperature below Mf, the parent phase transforms back to martensite, and the newly formed martensite is called M2. Upon heating part of the martensite transforms to parent phase with M1 martensite phase remains. M2 martensite phase forms upon cooling, domain walls 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 the 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 the last formed plate is the first to (Ref 10), and much more work to overcome the domain walls motion. So the release of the elastic strain energy and more work to overcome the motion of domain walls lead to the transformation of M1 shift to higher temperature and a kinetic stop appears upon heating.

4. Conclusions

In summary, by controlling the ratio of the cold deformation, the density of dislocations can be managed, and therefore the reverse transformation expands over a large temperature window. This is quite useful to output strains in a large temperature window comprising to conventional SMA composites interface which will be failure in the same temperature. As an example of applications in the so-called temperature memory effect, one do not have to embed SMAs into composites; instead, one just have to cold roll a curved surface NiTi alloy to above its recoverable limit to obtain a material with the ability of temperature memory in a wide temperature range, and the temperature memory effect was also confirmed to be operational in this wide temperature range.

Acknowledgments

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