Article ID: 1003 - 6326(2005)02 - 0336 - 04

Recovery stress characteristics of TiNi alloy wires after partial martensitic transformation under different constraint conditions①

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Abstract: The recovery stress characteristics of a TiNi shape memory alloy wire under different constraint conditions were studied. The results show that the recovery stress rate ($d\sigma/dT$) in the second heating cycle increases significantly with the increasing constraining-spring coefficient in the first heating cycle. As a result, a distinct discontinuity appears on the recovery stress curves of the TiNi alloy wires in the second heating process. Also, the results of differential scanning calorimeter(DSC) measurements show that after the thermomechanical process, the heating curve of the TiNi alloy wire consists of two independent endothermic peaks.

Key words: TiNi wire; partial transformation; recovery stress rate; bias spring
CLC number: TB381 **Document code:** A

1 INTRODUCTION

Shape memory alloys(SMAs) have attracted considerable attention for their novel performances, such as shape memory effect(SME), pseudoelasticity, high damping[1]. From the late 1980s, the recovery stress characteristics of SMAs attracted more and more attention. When prestrained and constrained SMA fibers are heated above the starting point of the reverse martensitic transformation, a large recovery stress can be generated. The value of the recovery stress can be influenced by many factors, such as chemical composition, heat treatment history, prestrain and external constraining condition of SMAs[2-5].

Recently, extensive researches have been devoted to the constrained martensitic transformation of shape memory alloys. Some investigations confirmed that partial transformation cycle could affect the transformation behavior of free state SMAs significantly[6-10], where a kinetic stop appears in the reverse transformation on the second heating cycle after a partial transformation cycle. The authors have done some researches on the partial transformation behavior of prestrained SMAs embedded into different matrices, including cement, metal and epoxy.[11-17]. Results show that, closely related to the micro-structural discontinuities of martensite, some discontinuities in the macroscopic properties of the SMAs can be observed. It has been confirmed that the strain-temperature curves of SMAs show a two-stage decrease after a previous partial transformation cycle[18, 19]. It is reasonable to assume that the recovery stress output is also affected by a previous partial transformation. However, to our knowledge, no such results have been systematically reported. In this paper, the effects of partial transformation on the recovery stress characteristics of a TiNi shape memory alloy coupled with springs were studied, and the mechanism behind the phenomenon was discussed.

2 EXPERIMENTAL

Commercial Ti-50.2% Ni alloy wires with 0.48 mm in diameter were obtained from the General Research Institute for Non-Ferrous Metals, China. The cold-drawn wires were vacuum aged at 873 K for 1.8 ks followed by cooling into ice water. The martensitic transformation starting and finishing temperature (M_s and M_f), the reverse martensitic transformation starting and finishing temperature (A_s and A_f) of the material determined by a differential scanning calorimeter(DSC) were 304, 287, 314 and 333 K, respectively. The wires were deformed in tension to 5% at the room temperature (293 K) and then coupled in serials with springs of different elastic coefficients, as shown in Fig. 1. Here the springs of different coefficient simulate the external constraints of different

① **Foundation item:** Project(50071037) supported by the National Natural Science Foundation of China; Project supported by the Scientific Research Foundation for the Returned Overseas Chinese Scholars, Education Ministry of China
Received date: 2004 - 11 - 25; **Accepted date:** 2005 - 01 - 18
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elastic modulii. The thermomechanical behaviors of the prestrained wires coupled with different bias springs were measured by a home built apparatus that can obtain the stress, strain and temperature data simultaneously.

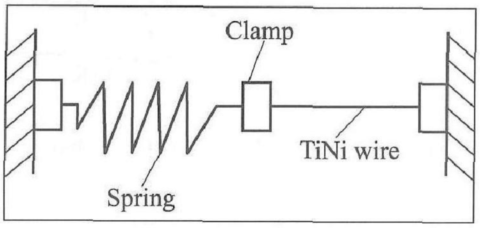

Fig. 1 Schematic diagram of experimental setup for TiNi alloy samples

The DSC specimens were spark cut from the wires. The DSC measurements were carried out using a TA INST 2910 DSC with a heating and cooling rate of 10 K/min. All specimens were cooled to 253 K before the DSC running.

3 RESULTS AND ANALYSIS

Fig. 2 shows the recovery stress vs temperature curves of the wires coupled with the springs of different coefficients. The recovery stresses start to increase quickly from around 340 K, which is higher than the A_s temperature possibly because of the release of the elastic strain energy by deformation[20, 21]. The recovery stresses stop increasing at a certain temperature and then remain horizontal, indicating the finish of the reverse martensitic transformation. One can see that the reverse transformation finishing temperature for the wires coupled with different springs increases with the increasing spring coefficient. The maximum output recovery stress also increases with the increasing spring coefficient. Upon cooling, the recovery stress first remains horizontal then starts to decrease at a temperature much lower than 340 K, resulting in a large hysteresis.

The heating processes of the wires in Fig. 2 were interrupted at 353 K, and then the temperature was cooled down below M_f. The strain vs temperature curves of the wires during this partial transformation cycle are shown in Fig. 3. It is seen that the recovery strain increases with the decreasing spring elastic coefficient during the heating process. Upon cooling, the martensitic transformation strain for the wires decreases with the increasing spring coefficient, as shown in Fig. 4. Obviously, some transformation strain remains in the wires at the end of the cooling process. On the next step the coupled springs were removed from the apparatus, and the strains of the wires were fixed. Therefore, some recovery stress will build

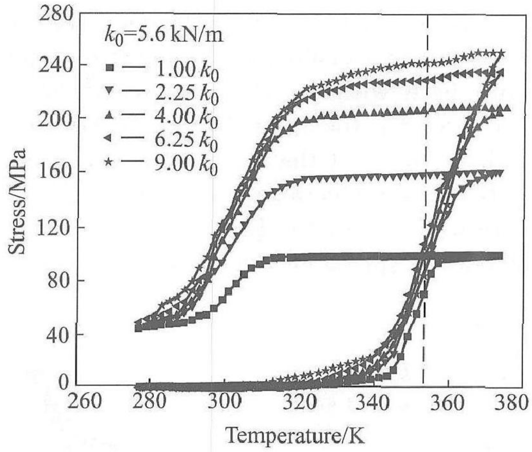

Fig. 2 Recovery stress vs temperature curves of wires coupled with springs of different elastic coefficients

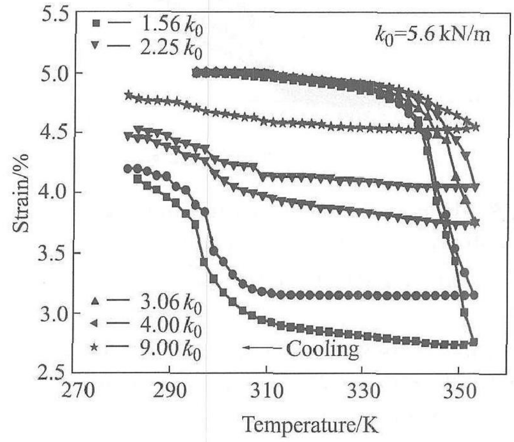

Fig. 3 Strain vs temperature curves of wires coupled with springs of different elastic coefficients

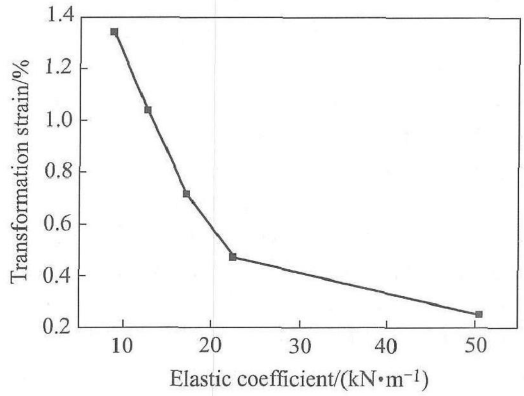

Fig. 4 Transformation strain as function of spring coefficient during cooling process of partial transformation cycle

up in the next heating process. Fig. 5 shows the recovery stress vs temperature curves of the wires during the constant constrained heating process. One can see that there is a two-stage rise in each curve. The first stages of different wires are separated from each other distinctly, and the recovery stress rate upon temperature ($d\sigma/dT$) increases with the decreasing spring coefficients. However, the second stages of different wires overlapped on the same path with the recovery stress rate ($d\sigma/dT$) are exactly the same. One can see that all these curves start at the same temperature 319 K, which is the A_s temperature of the wires. The temperature windows of the first stages decrease with the increasing spring elastic coefficient.

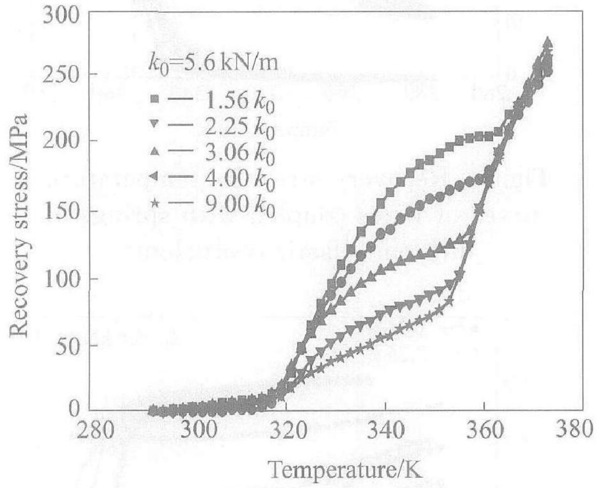

Fig. 5 Recovery stress vs temperature curves of wires during constant constrained heating process after partial transformation cycle

Fig. 6 shows the DSC results of the wires after the partial transformation cycle. It can be seen that there are two independent endothermic peaks in each curve. The peak temperatures of the lower temperature peaks decrease with the increasing spring coefficient, but the peak temperatures of the higher temperature peaks did not change their position. The enthalpies of the peaks in Fig. 6 are shown in Fig. 7. It can be seen that the area of the lower temperature peak decreases with the increasing spring coefficient, while the area of the higher temperature peak increases with the increasing spring coefficient.

The recovery stress characteristics in Fig. 5 can be explained by investigating the martensite formed after the first partial martensitic transformation. The martensite in the wires can be divided into two parts such as: the part that did not participate in the transformation during the partial thermal cycle, denoted here as M1, and the part that participated in the transformation, denoted here as M2. Obviously, the transformation strains in the M1 martensite for all 5% prestrained wires should be the same. It can be seen from Fig. 5 that during the second constant strain heating, the second stage of the recovery stress-temperature curves of all wires overlap on the same path. This path corresponds to the reverse transformation of M1. Fig. 6 also confirms that the transformation

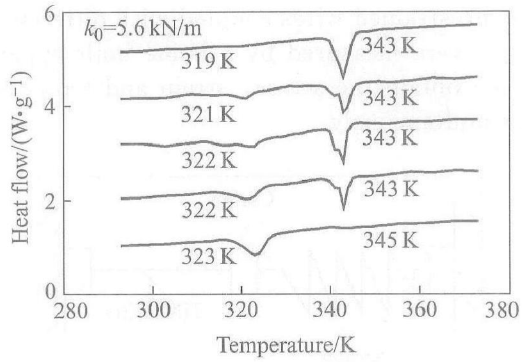

Fig. 6 DSC heating curves of wires after partial transformation while coupled with springs of different coefficients

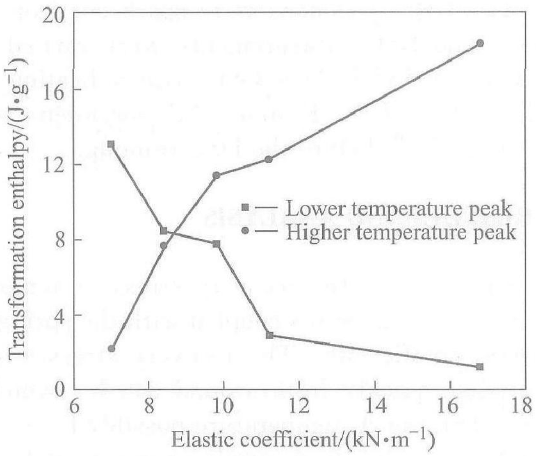

Fig. 7 Transformation enthalpy as function of spring coefficient

temperatures of the M1 martensite, corresponding to the higher temperature peaks, is basically unchanged, except that their transformation enthalpies decrease with the increasing spring coefficients. The M2 martensites in the wires coupled with different springs are different in two aspects: the volume fraction, and the transformation strain. When the heating process is interrupted at 353 K, the smaller the elastic coefficient of the springs, the larger the volume fraction of the parent phase which transforms from the martensite, as shown in Fig. 2. A larger parent phase fraction means that a larger fraction of the total transformation strain turns into elastic strain in the TiNi wire-spring system. During cooling, the parent phase transforms back to the martensite phase (the M2) under the tension of the springs. And the elastic strain of the wire-spring system will be restored as transformation strain in the newly formed martensite (M2). Consequently, more transformation strain is restored in the wires coupled with small coefficient springs than that in the wires coupled with large coefficient springs, as can be seen in Fig. 4. During the constant strain heating, a larger transformation strain means that the reverse transformation of the M2 martensite is accompanied with a larger recovery stress, as can be seen in Fig. 5. Therefore, the first stages of all curves in Fig. 5 are separated from each other.

The recovery stress rate upon temperature ($d\sigma/dT$) is an important parameter of the recovery stress curve, which is considered to be affected by chemical composition and prestrain level[5]. In this paper, however, experimental results show that with the same chemical composition and prestrain level, the SMA wires still show different recovery stress characteristics if the SMA wires have undergone a previous partial transformation, as can be seen in Fig. 5. Thus, the recovery stress characteristics can be tailored by a partial transformation cycle. The key point in this new design method is, according to the experimental results in this paper, that a larger recovery stress rate ($d\sigma/dT$) can be obtained through a partial transformation cycle constrained under a smaller constraining modulus.

4 CONCLUSIONS

The constraint conditions of TiNi shape memory alloy wires have a significant effect on the recovery stress characteristics in the following thermal cycles. The recovery stress rate in the following heating process increases with the decreasing constraining-spring coefficient in the first partial heating cycle. The discontinuity of recovery stress comes from the discontinuity of martensite. The newly formed martensite (M2) after a partial transformation cycle shows a larger recovery stress rate ($d\sigma/dT$) upon a smaller constraining-spring coefficient during the partial transformation cycle. The remained martensite (M1) that did not participate in the reverse transformation during the first thermal cycle shows a similar recovery stress behavior.

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(Edited by LONG Huai-zhong)