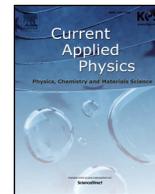




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## Damping and transformation behaviors of $\text{Ti}_{50}(\text{Pd}_{50-x}\text{Cr}_x)$ shape memory alloys with $x$ ranging from 4.0 to 5.0

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### ABSTRACT

The damping and transformation behaviors of  $\text{Ti}_{50}(\text{Pd}_{50-x}\text{Cr}_x)$  shape memory alloys with  $x$  ranging from 4.0 to 5.0 are systematically investigated. The damping capacity ( $Q^{-1}$ ) at the martensitic transformation is found to be inversely proportional to the square root of frequency, *i.e.*,  $Q^{-1} \propto \omega^{-0.5}$ . A relaxation peak or shoulder is observed slightly below the martensitic transformation damping peak for compositions within the compositional crossover region ( $4.5 \leq x \leq 4.8$ ). Furthermore, the damping capacity at the martensitic transformation is smaller within the compositional crossover region ( $4.5 \leq x \leq 4.8$ ), compared with that of compositions at both sides ( $x = 4.0$  and  $x = 5.0$ ). These observations can be ascribed to the hysteretic motion of interfaces between different phases near the compositional crossover region.

### 1. Introduction

The damping capacity ( $Q^{-1}$ ) represents the capacity of a material to convert the mechanical energy of vibration into heat [1–3]. To reduce the noise/vibration or absorb shock/impact, materials with high damping capacity are attracting much attention nowadays [4–9]. Shape memory alloys (SMAs) have been considered as promising candidates as they possess both high damping capacities and good mechanical properties [10,11].

It is known that SMAs undergo a reversible martensitic transformation between high-symmetry austenite (A) and low symmetry martensite (M) in response to the change in temperature or stress field [11]. As a result of the martensitic transformation, two types of internal planar interfaces exist in SMAs, including the phase front between A and M phases, and the twin boundaries between two different martensite variants [11]. The hysteretic motion of these planar interfaces always dissipates energy, giving rise to the high damping capacity in SMAs [12,13]. The damping source associated with the A/M phase front occurs during martensitic transformation [12–14]. The A/M interface is generally mobile but strongly dissipative, resulting in a high damping peak at the transformation temperature [12–14]. But such a damping peak depends sensitively on thermal gradients (*i.e.*, its damping value drops considerably when the temperature is fixed) and thus is a “transient peak” [12,14]. The other damping source appears in the martensite and is associated with the stress driven motion of twin

boundaries. Extrinsic defects (*e.g.* hydrogen), or intrinsic microstructure components (*e.g.* the twin junctions) interact with twin boundaries via either pinning/de-pinning [15,16] or jamming [17], and consequently lead to the dissipation of the mechanical energy. It is usually manifested as a “broad relaxation peak” after the martensitic transformation where martensite twins exist [6,18,19].

The twin boundary correlated damping capacity is thermal hysteresis free and independent on cooling/heating rate, thus is practically more applicable [6,8]. It has been shown that TiPd-based SMAs exhibit a “broad relaxation peak” or a high damping plateau within the ambient temperature range and could be good candidates for high damping materials [6,7,21]. The TiPd-based alloys is superior to TiNi-based alloy in the aspects of higher martensitic transformation temperature and larger size of twinning shear [7]. Recently, a small thermal hysteresis  $\Delta T$  was achieved in the compositional crossover region in  $\text{Ti}_{50}(\text{Pd}_{50-x}\text{Cr}_x)$  between two different martensitic transformations, as indicated by the solid circle in Fig. 1 (a) [20,22]. The two different martensitic transformations have opposite changes in electrical resistance at the transformation temperature [22]. The possible underlying reason for the small  $\Delta T$  is ascribed to the small interfacial strain at the austenite/martensite interface accommodated via coexistence of B19 and 9R martensites [22]. As damping capacity is closely related with the hysteretic motion of interfaces, it is then of interest to explore the damping behaviors at such a compositional crossover region.

In the present study, we thus systematically investigated the

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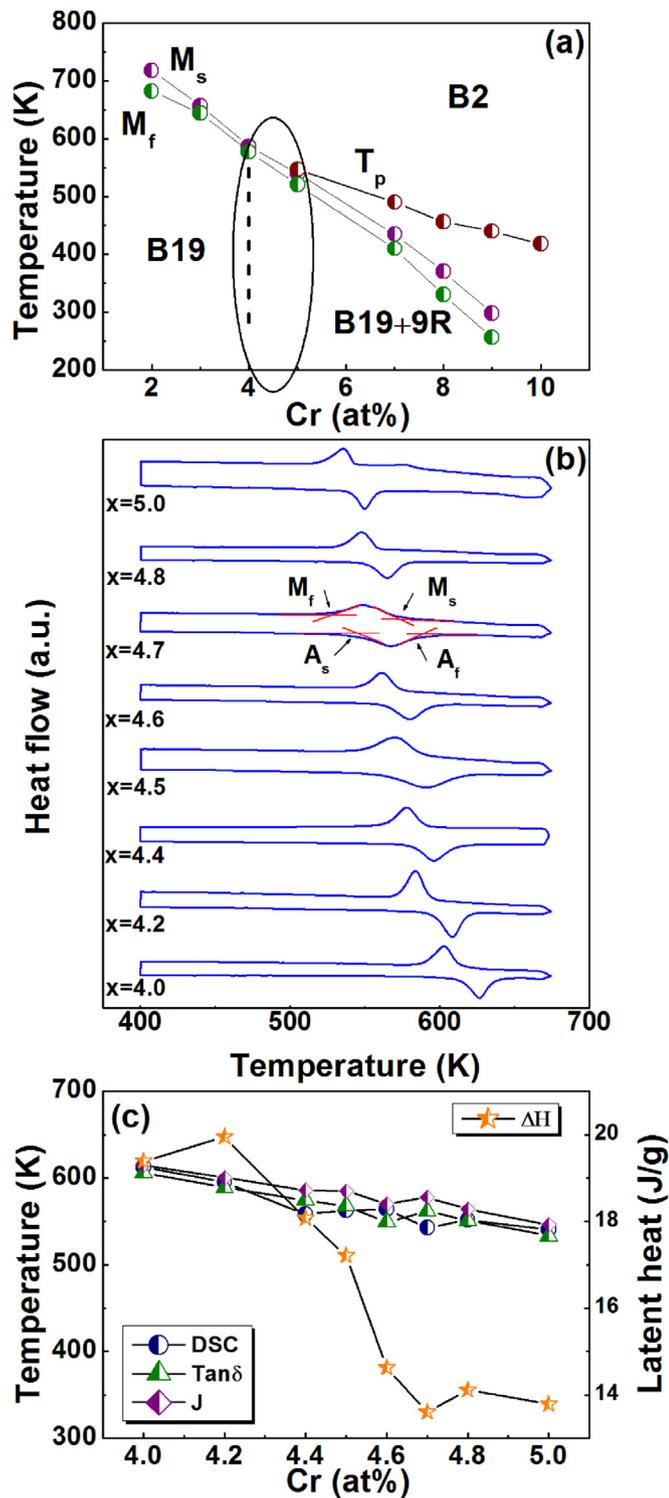


Fig. 1. (a) Phase diagram of  $Ti_{50}(Pd_{50-x}Cr_x)$ , after Enami et al. [20], with permission from publisher: ISIJ.  $M_s$  and  $M_f$  are the martensitic transformation start and finish temperatures, respectively.  $T_p$  is the temperature at which ER anomaly begins, defined in Ref. [20]. The solid circle indicates a crossover composition region, where the change in electrical resistance at the transformation temperature becomes opposite. (b) DSC results of  $Ti_{50}(Pd_{50-x}Cr_x)$  SMAs with  $x$  ranging from 4.0 to 5.0. Arrows indicate the  $M_s$ . (c) The  $M_s$  temperatures determined by DSC measurement, damping capacity ( $\tan\delta$ ) and storage compliance ( $J$ ) are plotted as a function of Cr concentration  $x$ . Moreover, the latent heat  $\Delta H$  during martensitic transformation as a function of Cr concentration  $x$  is shown as well.

damping capacity and phase transformation behaviors of  $Ti_{50}(Pd_{50-x}Cr_x)$  alloys with  $x$  ranging from 4.0 to 5.0 by differential scanning calorimeter (DSC) and dynamic mechanical analysis (DMA). The results show that the damping capacity at the martensitic transformation is inversely proportional to the square root of frequency ( $Q^{-1} \propto \omega^{-0.5}$ ). There exists a relaxation peak or shoulder slightly below the martensitic transformation damping peak within the compositional crossover region ( $4.5 \leq x \leq 4.8$ ). Furthermore, the damping capacity of martensitic transformation is found to be smaller within the compositional crossover region ( $4.5 \leq x \leq 4.8$ ) than that of compositions at both sides ( $x = 4.0$  and  $x = 5.0$ ). These observations can be ascribed to the hysteretic motion of interfaces between different phases near the compositional crossover region.

## 2. Experiment

Samples of  $Ti_{50}(Pd_{50-x}Cr_x)$  ( $x = 4.0, 4.2, 4.4, 4.5, 4.6, 4.7, 4.8, 5.0$  at%) alloys were prepared by arc melting a mixture of high purity metals (99.9% Ti, 99.9% Pd and 99.9% Cr) in an argon atmosphere. All the ingots were hot rolled to 1 mm thick. The specimens were then spark cut into suitable shapes for different experiments ( $3 \times 3 \times 1$  mm<sup>3</sup> for DSC and  $20 \times 2 \times 1$  mm<sup>3</sup> for DMA). They were then solution treated at 1273 K for 1 h in evacuated quartz tubes and quenched into ice water. In order to remove the affected surface layer, the specimens were mechanically polished.

DSC measurements were performed with a cooling/heating rate of 10 K/min between 400 K and 670 K to probe the martensitic transformation behaviors by exothermal/endothermic peaks. The damping properties ( $Q^{-1}$  or  $\tan\delta$ ) and the anelastic storage compliance ( $J$ ) were obtained by DMA using the single cantilever mode with displacement amplitude of 15  $\mu m$ , i.e., one end was fixed and stress field with sinusoid period (AC field) driven by Nitrogen gas was applied on the other end of the sample.

The temperature was chosen from 340 K to 635 K, the cooling/heating rate was fixed to 2 K/min and AC field frequencies were 0.2, 0.4, 1, 4, 10, 20 Hz, respectively.

## 3. Results

### 3.1. DSC results of $Ti_{50}(Pd_{50-x}Cr_x)$ with $x$ ranging from 4.0 to 5.0

DSC results of  $Ti_{50}(Pd_{50-x}Cr_x)$  SMAs with  $x$  ranging from 4.0 to 5.0 are shown in Fig. 1 (b). The exothermal/endothermic peaks in these DSC curves and the thermal hysteresis associated with the transformation ( $> 13$  K) suggest that all the  $Ti_{50}(Pd_{50-x}Cr_x)$  samples undergo a normal first order martensitic transformation. It is shown that with increasing Cr concentration  $x$ , the start temperature of martensitic transformation ( $M_s$ ), is reduced from 615 K of 4.0 Cr to 542 K of 5.0 Cr. Fig. 1 (c) plots the  $M_s$  as a function of Cr composition  $x$ . Such a composition dependence of transformation temperature is consistent with the reported phase diagram as shown in Fig. 1 (a). The corresponding transformation latent heat obtained from cooling processes decreases as well when Cr concentration  $x$  increases. However, there is an anomaly at  $x = 4.7$ , as shown in Fig. 1 (c). This phenomenon is in agreement with the  $\Delta T$  results, in which the  $\Delta T$  shows a minimum at  $x = 4.7$ , suggesting a possible composition crossover between two different transformations around  $x = 4.7$  [22].

Table 1 summarizes the phase transformation properties of  $Ti_{50}(Pd_{50-x}Cr_x)$  SMAs with  $x$  ranging from 4.0 to 5.0, including the martensitic transformation start and finish temperatures ( $M_s$  and  $M_f$ ), the reverse transformation start and finish temperatures ( $A_s$  and  $A_f$ ), thermal hysteresis ( $\Delta T = \frac{1}{2}(A_s + A_f - M_s - M_f)$ ), and latent heat ( $\Delta H$ ).

### 3.2. Damping capacities of $Ti_{50}(Pd_{50-x}Cr_x)$ with $x$ ranging from 4.0 to 5.0

In this subsection, we investigated the damping capacities of all the

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