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Room-temperature phases observed in $Ti_{53-x}Ni_{47}Zr_x$ high-temperature shape memory alloys

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Abstract

 $Ti_{53-x}Ni_{47}Zr_x$ (x=5~20 at %) shape memory alloys exhibit martensitic transformation characteristics and their transformation temperatures increase linearly with increasing Zr content. There are three different phases observed in 900°C homogenized alloys for Zr content ≥ 10 at %, including the grey (Ti,Zr)Ni matrix, the black $(Ti,Zr)_2Ni$ particles and the white λ_1 phase. But only the former two phases are found in the $Ti_{48}Ni_{47}Zr_5$ alloy. DTA test results show that the homogenized $Ti_{38}Ni_{47}Zr_{15}$ alloy has three endothermic peaks in the thermograph, in which the 930°C endothermic peak is associated with the solid \leftrightarrow liquid transition of λ_1 phase, the peak at 990°C is associated with the reverse peritectic transformation of $(Ti,Zr)Ni\rightarrow$ Iiquid and the one at 1160°C is the dissolution reaction of the (Ti,Zr)Ni \rightarrow Iiquid. © 1998 Elsevier Science S.A.

Keywords: $Ti_{53-x}Ni_{47}Zr_x$ shape memory alloys; (Ti,Zr)Ni phase; (Ti,Zr)₂Ni phase; λ_1 phase; Peritectic reaction

1. Introduction

Shape memory alloys (SMAs) with Ms temperature¹ higher than 100°C have drawn much attention recently. It is well known that $Ti_{50}Ni_{50-y}X_y$ ternary SMAs with X= Pd, Pt or Au have a Ms temperature much higher than 100°C and exhibit an one-way shape memory effect [1–4]. However, the high cost of precious metals will limit the practical applications of these SMAs. For this reason, other ternary TiNiX SMAs with lower costs need to be investigated. Among them, the most prospective candidates are TiNiZr and TiNiHf alloys with Zr and Hf being used to replace Ti in these alloys.

Eckelmeyer [5] showed that a small amount of Ti replaced by Zr in the $Ti_{50}Ni_{50}$ alloy can raise the Ms temperature in TiNiZr SMAs. In 1990, Krupp et al. obtained a patent on TiNiZr SMAs with As temperature² ranging from 108°C for 10.8 at % Zr to 170°C for 20.2 at % Zr [6]. In 1992, Mulder et al. [7] reported that the Ms

temperatures above 120°C can be obtained in TiNiZr alloys with Zr content above 10 at % and Ni content below 49.5 at %. They also studied the microstructures of parent and martensitic phases in these alloys by optical and electron microscope and found $(Ti,Zr)_2Ni$ precipitates exist in these alloys. In 1995, Meisner reported that $(Ti,Zr)_2Ni_7$, $(Ti,Zr)_7Ni_{10}$ and NiZr phases can be observed in Ni-rich $Ti_{50-x}Ni_{50}Zr_x$ alloys with the Zr content in the range of 30-50 at % at room temperature [8].

For Ti-rich TiNi binary alloys, a peritectic reaction of liquid + TiNi \rightarrow Ti₂Ni occurs during the solidification. Therefore, a relatively large volume fraction of Ti₂Ni particles forms in these alloys, which in turn affects the mechanical strength and formability of Ti-rich TiNi binary alloys [9,10]. This peritectic reaction may also occur in ternary TiNiZr alloys. However the effect of Zr content on the characteristics of this peritectic reaction in ternary TiNiZr alloys is still not clarified. Furthermore, phases other than (Ti,Zr)₂Ni in TiNiZr SMAs can also possibly form. Since the shape memory behaviour of a SMA is strongly dependent on its microstructure, it is important to know what microstructural evolution occurred in this SMA. The aim of the present work is to investigate the characteristics of peritectic reaction associated with the $(Ti,Zr)_2$ Ni phase in Ti-rich $Ti_{53-x}Ni_{47}Zr_x$ alloys with x =

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¹Ms means the starting temperature of martensitic transformation, and As means the starting temperature of reverse martensitic transformation.

²Ms means the starting temperature of martensitic transformation, and As means the starting temperature of reverse martensitic transformation.

 $5 \sim 20$ at %. The observed phases excluding the $(Ti,Zr)_2Ni$ in these Ti-rich TiNiZr alloys are also discussed in this study.

2. Experimental procedure

The conventional tungsten vacuum arc melting technique was employed to prepare $Ti_{53-x}Ni_{47}Zr_x$ (x=5, 10, 15, 20 at %) alloys. The symbols Zr_5 , Zr_{10} , Zr_{15} and Zr_{20} are hereinafter used to denote specimens of Ti₄₈Ni₄₇Zr₅, $Ti_{43}Ni_{47}Zr_{10}$, $Ti_{38}Ni_{47}Zr_{15}$ and $Ti_{33}Ni_{47}Zr_{20}$ alloys, respectively. Titanium (purity: 99.9%), nickel (purity: 99.9%) and zirconium (purity: 99.8%), totalling about 100 g, were melted and remelted at least six times in an argon atmosphere. Pure titanium button was also melted and used as a getter. The mass loss during the melting was negligibly small. The as-melted buttons were homogenized holding at 900°C for 72 h and furnace-cooled. The homogenized buttons were cut into several plates with a low speed diamond saw. In order to identify phases, some of the cut plates were heated up to 950°C and 1000°C, respectively, and then quenched in liquid nitrogen. The acquired specimens were polished for DSC/DTA measurements and EPMA examination.

DSC measurement was conducted by a Dupont 2000 thermal analyzer equipped with a quantitative scanning system 910 DSC cell for controlled heating and cooling runs on a sample encapsulated in an aluminum pan. The running temperature range was from 0°C to 400°C with a heating/cooling rate of 10°C min⁻¹. The continuous heating experiments were conducted using a differential thermal analyzer (DTA) in which a bulk sample was analyzed in an Al₂O₃ crucible using a Dupont 2000 DTA under a flowing purified argon atmosphere. The running temperature range was from 800°C to 1250°C with a heating rate of 10°C min⁻¹. Microstructure observations employed JEOL JXA-8600 SX EPMA, which was utilized to take the image, line-scanning profiles (LSPs) and quantitative chemical compositions. The EPMA was operated at 15 kV with a probe current 100 nA.

3. Experimental results and discussion

3.1. The transformation behaviours of $Ti_{53-x}Ni_{47}Zr_x$ shape memory alloys

Fig. 1 shows the experimental results of DSC measurements for the homogenized Zr₅, Zr₁₀, Zr₁₅ and Zr₂₀ alloys, respectively, in both forward and reverse transformations. Peaks appearing in Fig. 1 are identified as being associated with the martensitic transformation of $B2\leftrightarrow B19'$ [7]. The transformation peak temperatures versus Zr-content shown in Fig. 1 is plotted in Fig. 2. From Fig. 2, it is clear that the transformation peak temperatures increase linearly from

Fig. 1. DSC curves of homogenized $Ti_{53-x}Ni_{47}Zr_x$ (x=5-20 at %) alloys in which M* and A* are peak temperatures of forward and reverse martensitic transformations, respectively.

50°C to 300°C with increasing Zr content. Therefore, based on the results of Fig. 2, a TiNiZr SMA alloy with the desired transformation temperature can be obtained by carefully controlling its corresponding Zr content. The more detailed shape memory properties of Ti_{53-x}Ni₄₇Zr_x



10

Zr (at%)

20

0

n





alloys after different thermomechanical processes are reported in other investigations [11].

3.2. The phases in homogenized specimens

Fig. 3a-d show the EPMA back-scattering electron images(BEIs) of 900°C homogenized Zr5, Zr10, Zr15 and Zr₂₀ alloys, respectively. Because the intensity of the back-scattering electron is proportional to the atomic number of the individual element in the illuminated area, the brighter areas in Fig. 3 indicate the regions of the higher Zr content. On the contrary, the darker ones have the higher Ti content. It is clear that there are three different contrast areas, including the grey matrix, the darker (i.e. black) particles and the brighter (i.e. white) ones, coexisting in the alloys of Zr content ≥ 10 at %, as shown in Fig. 3b-d. Only black particles located around the grain boundaries appear in the Fig. 3a of Zr₅ alloy. Noted that the white particles in Fig. 3d are not so clear as those shown in Fig. 3b and c because the difference of Zr (at %) content between white particles and grey matrix in

Table 1 The compositional analyses for 900°C homogenized $Ti_{53-x}Ni_{47}Zr_x$ (x=5–20 at %) alloys

| 900°C×72 h homogenized specimens (in at %) | | | | | |
|--------------------------------------------|-----------------------|----------------|----------------|---------------|--|
| | | Ti | Ni | Zr | |
| Zr ₅ | М | 46.5±0.3 | 48.4±0.3 | 5.1±0.2 | |
| | S ₁ | 62.3 ± 0.3 | 32.8 ± 0.3 | 4.9 ± 0.2 | |
| | S ₂ | _ | _ | _ | |
| Zr ₁₀ | Μ | 42.1 ± 0.3 | 48.4 ± 0.3 | 9.5±0.3 | |
| | S ₁ | 58.4 ± 0.4 | 32.9 ± 0.3 | 8.7 ± 0.4 | |
| | S ₂ | 43.8±0.3 | 36.8±0.4 | 19.4±0.3 | |
| Zr ₁₅ | M | 37.3±0.4 | 48.2 ± 0.3 | 14.5±0.3 | |
| | S ₁ | 53.2 ± 0.4 | 33.1 ± 0.4 | 13.7±0.3 | |
| | S ₂ | 40.4 ± 0.3 | 37.3±0.4 | 22.3±0.3 | |
| Zr ₂₀ | M | 31.7±0.4 | 48.5 ± 0.3 | 19.8±0.3 | |
| | S ₁ | 48.7 ± 0.3 | 33.5 ± 0.4 | 17.8±0.4 | |
| | \mathbf{S}_{2}^{T} | 37.8±0.3 | 37.5±0.3 | 24.7±0.3 | |

M: Matrix; S₁: Black precipitate; S₂: White precipitate.

the Zr_{20} alloy is smaller than that in the Zr_{10} and Zr_{15} alloys, as shown in Table 1.

The chemical compositions of these particles and matrix



Fig. 3. The EPMA back-scattering electron images (BEIs) of 900°C homogenized $Ti_{53-x}Ni_{47}Zr_x$ alloys with (a) Zr=5,(b) Zr=10,(c) Zr=15,(d) Zr=20.

determined by the EPMA Wave Dispersed Spectrometer (WDS) are shown in Table 1. In Table 1, the ratio of (Ti+Zr)/Ni in the matrix, black particles and white ones are about 1, 2 and 1.7, respectively. Compared with the Ti-Ni binary phase diagram [12], the results of Table 1 indicate that the grey matrix in Fig. 3 is the (Ti,Zr)Ni phase and the black particles are the (Ti,Zr)₂Ni phase. Here, the Zr atoms replace Ti atoms in Ti_{53-x}Ni₄₇Zr_x alloys due to the isomorphologic solid solution effects of Ti and Zr atoms in Ti–Zr binary phase diagram [13]. The white particles in Fig. 3 should be a new Ti-Ni-Zr ternary phase due to the lack of Ti_{1.7}Ni phase in the Ti-Ni binary diagram and Zr_{1.7}Ni phase in Zr–Ni binary diagram [14]. In order to clarify the relations among these three phases, a further experiment is conducted in Section 3.3. In this experiment, only the Zr₁₅ alloy is selected because the microstructural morphologies of Zr₁₀, Zr₁₅ and Zr₂₀ alloys are very similar.

Fig. 4 is the BEI with Ti, Ni and Zr line-scanning profiles for the Zr_{15} alloy homogenized at 900°C for 72 h. Note that the Ni concentration decreases in both black and white particles to almost the same extent. However, the black particles have higher Ti and lower Zr contents than the white particles. The primary difference between the black and white particles is thus their Ti/Zr ratio. The compositional partition phenomena [15] of Ti and Zr elements in both particles is why they have a distinct contrasting image in the observed microstructures of Figs. 3 and 4.

According to the 700°C Ti–Ni–Zr ternary isotherm diagram proposed by Eremenko et al. [16], there is a ternary λ_1 phase (Laves phase with MgZn₂ type structure) existing in the Ti–Ni–Zr ternary alloy system. Based on the data of Table 1, the average compositional loci of phases existing in Fig. 3 can be plotted on a 700°C ternary Ti–Ni–Zr Eremenko's isotherm, as shown in Fig. 5. Fig. 5

Fig. 4. The BEI with Ti, Ni and Zr line-scanning profiles for $Ti_{38}Ni_{47}Zr_{15}$ alloy homogenized at 900°C×72 h.



Fig. 5. The 700°C Ti–Ni–Zr Eremenko's isotherm diagram with some boundary shift of those domains near $Ti_{50}Ni_{50}$ corner (indicated by the dotted lines) can be used to be the 900°C isotherm for $Ti_{53-x}Ni_{47}Zr_x$ specimens.

clearly shows that the grey matrix, black and white particles in Fig. 3 should be the δ_1 (TiNi-base B2 phase), η (Ti₂Ni-base phase) and λ_1 (TiNiZr ternary phase) phases, respectively. In this analysis, we suggested that the 700°C Ti–Ni–Zr isotherm diagram near the Ti₅₀Ni₅₀ corner is still suitable for the 900°C homogenized specimens except for a slight boundary shift of the domains η , $\eta + \delta_1$, $\eta + \lambda_1$, $\delta_1 + \eta + \lambda_1$, $\delta_1 + \eta + \lambda_1$, λ_1 etc., as indicated in the broken lines in Fig. 5.

3.3. The DTA thermograph of Zr_{15} alloy and the characteristic of each phase

In order to understand the characteristics of the above mentioned three phases, a DTA analysis was conducted on the homogenized Zr_{15} alloy, as shown in Fig. 6. In Fig. 6, three endothermic peaks appear at about 930°C, 990°C, and 1160°C, respectively. To understand the phase transformation related to each peak of Fig. 6, some specimens of Zr_{15} alloy were heated up to 950°C or 1000°C. The experimental results are discussed as follows.



Fig. 6. DTA thermograph of the 900°C homogenized Ti₃₈Ni₄₇Zr₁₅ alloy.

3.3.1. The characteristic of λ_1 -phase

In order to reveal which phase transition is associated with the 930°C endothermic peak shown in Fig. 6, one homogenized Zr_{15} specimen was heat-treated at 950°C for 2 h and then quenched in liquid nitrogen. The microstructure of this specimen observed by BEIs of EPMA is shown in Fig. 7. As the specimen was heated to 950°C, it was discovered that a small amount of liquid phase flowed out on this specimen's surface, indicating that the 930°C phase transition involves a liquid phase reaction.

As seen in Fig. 7a, the (Ti,Zr)Ni grains have obviously grown and they are larger than the as-homogenized ones shown in Fig. 3c. In Fig. 7a, the morphology of the black $(Ti,Zr)_2Ni$ particles remains unchanged just as the ashomogenized ones. Only the white λ_1 particles change their morphology and spread out along (Ti,Zr)Ni grain boundaries due to their changing into a liquid phase at





Fig. 7. (a) The EPMA back-scattering electron image, and (b) Ti, Ni and Zr line-scanning profiles, of $Ti_{38}Ni_{47}Zr_{15}$ alloy heat-treated at 950°C for 2 h and then quenched in liquid nitrogen.

950°C. Fig. 7b shows the Ti, Ni and Zr line-scanning profiles (LSPs) on the microstructure of Fig. 7a. Obviously, these elemental concentration profiles are very similar to those of the homogenized ones of Fig. 4. The composition of the white particles detected by the EPMA WDS is consistent with that of λ_1 phase. Therefore, the phase liquefied at 950°C should be the λ_1 phase and the 930°C endothermic peak occurring in Fig. 6 is associated with the solid \leftrightarrow liquid transition of λ_1 phase.

There are some black (Ti,Zr)₂Ni particles that have been trapped inside the (Ti,Zr)Ni grains, as shown by the single arrows in Fig. 7a. This phenomenon is quite different from that exhibited in 900°C homogenized specimens of Fig. 3(c) in which all particles are located around the (Ti,Zr)Ni grain boundaries. It is speculated that these particles trapped inside the (Ti,Zr)Ni grains and without contacting the liquid phase were produced by the rapid moving velocity of (Ti,Zr)Ni grain boundary at a high temperature. The higher the heating temperature, the larger the growth rate of (Ti,Zr)Ni grains and the faster the moving velocity of (Ti,Zr)Ni grain boundaries. Thus, if the (Ti,Zr)₂Ni particles can not move in the same direction as the moving (Ti,Zr)Ni grain boundaries, they will be trapped inside the (Ti,Zr)Ni grains, as those mentioned above. Certainly, the liquid λ_1 phase can move rapidly due to its fluidity. Therefore, some of (Ti,Zr)₂Ni particles can move with the flowing liquid and then be confined locally at (Ti,Zr)Ni grain boundaries after the specimen has cooled down, as shown by the double arrows in Fig. 7a.

3.3.2. The characteristic of (Ti,Zr)₂Ni phase

In order to clarify what reaction is associated with the 990°C endothermic peak of Fig. 6, another homogenized Zr_{15} specimen was heated at 1000°C for 1.5 h and then quenched in liquid nitrogen. The microstructure of this specimen observed by BEIs of EPMA is shown in Fig. 8. In Fig. 8, the black particles have been proven by the EPMA WDS analysis to be the $(Ti,Zr)_2Ni$ phase $(Ti_{53.92}Ni_{32.35}Zr_{13.73})$. Obviously, there are two different morphologies of trapped black particles coexisting in Fig. 8a. One is the isolated black $(Ti,Zr)_2Ni$ particles in the (Ti,Zr)Ni grain or in the λ_1 phase at (Ti,Zr)Ni grain boundaries, as shown by the single arrows in Fig. 8a. The other is the massive agglomerate of $(Ti,Zr)_2Ni$ particles surrounded by a liquid phase, as shown by the double arrows in Fig. 8a.

By comparing with Figs. 7 and 8, it is known that the (Ti,Zr)Ni grains have grown more significantly at 1000°C. In Fig. 8a, most of the isolated $(Ti,Zr)_2Ni$ particles and the massive agglomerates of $(Ti,Zr)_2Ni$ particles are trapped inside the giant (Ti,Zr)Ni grains. This is the major difference in microstructures between the specimen held at 950°C for 2 h and that held at 1000°C for 1.5 h, as seen in Figs. 7 and 8.

According to the Ti–Ni binary phase diagram [12], there is a TiNi+Liq. \leftrightarrow Ti₂Ni peritectic reaction existing at the





| 1000°C×1.5 h and liquid nitrogen N_2 quenching (in at %) | | | | | | |
|------------------------------------------------------------|-------|-------|-------|------------------------------------|--|--|
| Location | Ti | Ni | Zr | Remark | | |
| 1 | 37.18 | 48.34 | 14.48 | (Ti,Zr)Ni matrix | | |
| 2 | 37.03 | 48.17 | 14.80 | (Ti,Zr)Ni matrix | | |
| 3 | 54.29 | 32.05 | 13.65 | (Ti,Zr) ₂ Ni | | |
| 4 | 54.35 | 32.03 | 13.62 | (Ti,Zr) ₂ Ni | | |
| 5 | 53.92 | 32.35 | 13.73 | (Ti,Zr) ₂ Ni | | |
| 6 | 49.92 | 31.77 | 18.31 | (Ti,Zr) ₂ Ni decomposed | | |
| 7 | 50.25 | 31.88 | 17.87 | (Ti,Zr) ₂ Ni decomposed | | |
| 8 | 45.62 | 31.92 | 22.46 | (Ti,Zr),Ni decomposed | | |
| 9 | 31.27 | 34.00 | 34.73 | liquid | | |
| 10 | 35.02 | 33.01 | 31.97 | liquid | | |
| 11 | 41.86 | 34.61 | 23.53 | liquefied λ_1 | | |
| 12 | 41.96 | 34.28 | 23.76 | liquefied λ_1 | | |
| 13 | 53.67 | 32.25 | 14.08 | isolated (Ti,Zr),Ni | | |
| 14 | 54.01 | 32.30 | 13.69 | isolated (Ti,Zr) ₂ Ni | | |



Fig. 8. (a) The EPMA back-scattering electron image, and (b) the locations of compositional analyses shown by arrows, for $Ti_{38}Ni_{47}Zr_{15}$ alloy heat-treated at 1000°C for 1.5 h and then quenched in liquid nitrogen.

985°C isotherm. Thus, we expected that (Ti,Zr)₂Ni particles have decomposed into (Ti,Zr)Ni+Liq. by the reverse peritectic reaction when the specimen was held at 1000°C for 1.5 h. Fig. 8b clearly shows that several (Ti,Zr)₂Ni particles have decomposed in an agglomerate. This feature indicates that the 990°C endothermic peak appearing in Fig. 6 is associated with the reverse peritectic reaction of $(Ti,Zr)_2Ni \rightarrow (Ti,Zr)Ni + Liq$. However, there are still many black (Ti,Zr)₂Ni particles retained in this agglomerate. It is reported that the time needed for the completion of the peritectic reaction is a function of the undercooling degree and of the solute diffusion coefficient [17]. We suggest that this phenomena may also occur in the reverse peritectic transformation of (Ti,Zr)₂Ni particles which need a rather long time to fully decompose at 1000°C due to the small superheating in this study.

The numbers #1-#14 shown by arrows in Fig. 8b

indicate the locations of compositional analyses by EPMA WDS. The acquired compositions are shown in Table 2. The last column of Table 2 also shows the corresponding phase of each location, estimated from the Ti-Ni-Zr ternary isotherm of Fig. 5 and the analytic results of Section 3.2. For examples, in Fig. 8b, the grey matrix (#1-#2), the black particles (#13-#14) and the continuous white zone (#11-#12) are the (Ti,Zr)Ni phase, $(Ti,Zr)_2$ Ni phase and liquefied λ_1 phase, respectively. The black areas (#3-#5) and the grey ones (#6-#8) in the agglomerate are still the (Ti,Zr)₂Ni phase with the former ones having a lower Zr% than the latter ones. The brightest location (#9-#10) showing much higher Zr% (about 32 at %) is also a liquid phase at 1000°C and is distinguishable from the liquefied λ_1 phase (#11-#12) in which the Zr content is around 22 at %-23 at %, as indicated in Tables 1 and 2.

Based on the data of Table 2, the phases existing inside the agglomerate do not include (Ti,Zr)Ni phase and all the phases show a lower Ni content than their original ones in Table 1. This feature indicates that the new (Ti,Zr)Ni phase forms during the reverse peritectic reaction and it grows on the interface of the original (Ti,Zr)Ni matrix. Meanwhile, the interdiffusion of Ti, Ni and Zr atoms among (Ti,Zr)₂Ni, (Ti,Zr)Ni and liquid phases during the reverse peritectic reaction make the (Ti,Zr)₂Ni and liquid phases decrease their Ti and Ni content but increase their Zr content, as seen with locations #6-#8 for the former and locations #9-#10 for the latter in Fig. 8b. In Fig. 8b, some isolated (Ti,Zr)₂Ni particles (#13-#14) do not occur the reverse peritectic reaction even when the specimen has been heated up to 1000°C. From Table 1, it is known that the composition of (Ti+Zr) in (Ti,Zr)₂Ni particles exhibit a small fluctuation (about 0.8 at %) which makes different (Ti,Zr)₂Ni particles have different melting points. We suggest that this compositional fluctuation in these particles accounts for the reason why some of $(Ti,Zr)_2Ni$ particles decomposed by the reverse peritectic reaction at 1000°C, but the others do not decompose in Fig. 8.

The endothermic peak at 990°C is not as sharp as the one at 930°C in Fig. 6 because the volume fraction occupied by $(Ti,Zr)_2Ni$ particles is less than that of λ_1 phase in Fig. 3(c) and the reverse peritectic reaction of $(Ti,Zr)_2Ni$ may proceed gradually, not like the λ_1 phases which can dissolve quickly at 930°C.

3.3.3. The characteristic of (Ti,Zr)Ni phase

Concerning the endothermic peak appearing at 1160° C in Fig. 6, we suggest that it is the dissolution reaction of the (Ti,Zr)Ni \rightarrow Liquid. From a thermodynamic point of view, the solid-soluted impurity will lower the melting point of the original pure material. This phenomenon should also occur in Zr soluted TiNi alloys, in which the melting point of TiNi is 1312° C [12], but that of (Ti,Zr)Ni is around 1160° C.

4. Conclusion

- 1. $\text{Ti}_{53-x}\text{Ni}_{47}\text{Zr}_x$ (x=5-20 at %) alloys exhibit martensitic transformation characteristics, in which the DSC transformation peak temperatures increase linearly from 50°C to 300°C with increasing Zr content.
- 2. There are three different phases in 900°C homogenized $\text{Ti}_{53-x}\text{Ni}_{47}\text{Zr}_x$ alloys for Zr content ≥ 10 at %. They are the grey (Ti,Zr)Ni matrix, the black $(\text{Ti},\text{Zr})_2\text{Ni}$ particles and the white λ_1 phase. However, only the former two phases are found in the Ti₄₈Ni₄₇Zr₅ alloy.
- 3. There are three endothermic peaks in the DTA thermograph of the homogenized $Ti_{38}Ni_{47}Zr_{15}$ alloy. The peak at 930°C is associated with the solid \leftrightarrow liquid transition of λ_1 phase. The peak at 990°C is associated with the reverse peritectic transformation of $(Ti,Zr)_2Ni\rightarrow(Ti,Zr)Ni+Liq$. The peak at 1160°C is the dissolution reaction of $(Ti,Zr)Ni\rightarrow$ Liquid.

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