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Martensitic transformation behaviors of Ti-rich Ti–Ni alloy fibers fabricated by melt overflow

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ABSTRACT

$Ti_{50}Ni_{50}$, $Ti_{50.5}Ni_{49.5}$, $Ti_{51}Ni_{49}$ and $Ti_{51.5}Ni_{48.5}$ fibers were fabricated by melt overflow process. The rapid solidification can increase the solubility above the equilibrium solubility. The effects of the rapid solidification of Ti-rich Ti–Ni alloys on the microstructure, transformation temperatures and shape memory characteristics are investigated. The addition of 0.5 at.% Ti in $Ti_{50}Ni_{50}$ alloy greatly increases the transformation temperature. However, the transformation temperatures decrease again for Ti content exceeding 51 at.%. Results of thermal cycling tests under various constant stress levels reveal that the recoverable elongation associated with B2–B19 martensitic transformation of $Ti_{50.5}Ni_{49.5}$ fibers is two times larger than that of $Ti_{51.5}Ni_{48.5}$ alloy fiber.

1. Introduction

Ti–Ni alloys are the most successful shape memory alloys due to their unique functional properties, which make them highly attractive for many applications including thermal and mechanical actuators and biomedical applications [1,2]. Their additional distinctive characteristics such as good ductility, high corrosion and fatigue resistance besides great damping capability and considerable strength and toughness have led to various commercial applications in different industrial fields [3]. Practically martensitic transformation determines almost all important properties of shape memory alloys, including shape memory effect and superelasticity. Transformation temperature determines at what temperature such effects can be observed. For shape memory applications, therefore, the transformation temperature control is very important [4]. Martensitic transformation temperature is strongly dependent on alloying. Then there has been much effort to modify Ti–Ni alloys by adding various alloying elements to the binary system. Recently shape memory alloys operating at high environmental temperatures have attracted attention as solid-state actuators for use in aircraft engines, automobile engines and energy-generation systems [5,6]. It is reported that the martensitic transformation temperatures increase with the replacement of Ni with Pd and Pt above a critical concentration [7,8]. Ti–Ni–Hf and Ti–Ni–Zr alloys also exhibits high transformation temperatures. However, their applications are limited because of the high cost of precious metal alloying elements for Ti–Ni–Pd and Ti–Ni–Pt alloys and the low ductility and poor cold-workability for Ti–Ni–Hf and Ti–Ni–Zr alloys [9].

Even though adding alloy element and thermomechanical treatment can change the transformation temperature. It is well known that martensitic transformation temperature is also dependent on composition in Ti–Ni binary alloys. The transformation temperature is strongly dependent on Ni concentration. In Ni-rich side of Ti–Ni alloy system, one percent addition of Ni content can change the transformation temperature by more than 100 °C. On Ti-rich side, however, the martensitic transformation start temperature is almost composition independent being about 60 °C. This may be due to the fact that the solubility limit of TiNi intermetallic phase on Ti-rich side is almost vertical and thus it is not possible to get Ti-rich TiNi solid solution. Therefore, the Ti-rich alloys show a behavior being the same as $Ti_{50}Ni_{50}$ alloy [10].

Generally there are four advantages of rapid solidification over the conventional solidification. These are an ability to form metastable phase, increasing the solubility above the equilibrium solubility, decreasing the segregation of element additions, and refining the microstructure. Then it is possible to make the supersaturated TiNi intermetallic phase by the rapid solidification. These make possible to study the effect of Ti content on martensitic transformation temperature in Ti-rich side of Ti–Ni alloy system. In the present study, the effects of the rapidly solidified microstructures in Ti-rich Ti–Ni alloys on transformation temperatures were investigated in order to enhance their high temperature functional performance.

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2. Experimental

Mother alloys with the nominal composition of $Ti_{50+x}Ni_{50-x}$ (x = 0, 0.5, 1.0 and 1.5) were prepared from high purity elements of nickel and sponge titanium by arc melting in a water-cooled Cu hearth. The alloys were re-melted several times under the high purity of argon atmosphere to ensure the homogeneity. The experimental studies have been performed using a laboratory scale arc melt overflow device. About 40 g of mother alloys was placed in a water-cooled hearth and skull melted under argon atmosphere by plasma beam just same as arc melting. Then, the hearth was tilted about the rotating quenching wheel made of molybdenum. The liquid metal had overflowed over a relatively horizontal edge or pour spot to contact the cooling wheel surface. The quenching wheel substrate served as a continuous permanent mold against which the casting had solidified. The thickness of fibers can be controlled by the rotating speed of the wheel. Clearly, a wide range of metallic fiber, filament, ribbon or strip can be cast by modifying the basic melt overflow system. The dimension of Mo cooling wheel is 122 mm in the diameter and 10 mm wide. In order to be produced in the shape of fibers or filaments, its tip was acutely machined. The linear speed of the wheel was kept at 5.1 m/s (1000 rpm) to produce relatively thin fibers. Then the fibers with 200 mm width and about 100 μm thickness were cast as shown in Fig. 1.

Fig. 1. Photograph of as-cast Ti–Ni fibers fabricated by melt overflow process.

Microstructural and compositional investigations were performed by scanning electron microscopy (SEM) using a ZEISS (SUPER555VD) instrument and by energy dispersive X-ray spectrum (EDS) using a NORAN (THERMO Scientific Ultradry) instrument. Phase constitutions were determined by X-ray diffraction (XRD) analysis using Cu Kα radiation. Shape memory behavior was characterized by thermal cycling under various constant tensile stress levels. During each cycle, tensile samples were first heated to a temperature well above austenite transformation finish temperature (A_f), and then a predefined stress was applied. The stressed sample was then cooled to a temperature well below martensitic transformation finish temperature (M_f) and then heated again to a temperature above A_f; this completed one cycle under a predefined stress level. At this point the next level of stress was applied, and the thermal cycle repeated again until the end of the cycle experiment.

3. Results and discussion

SEM images of Fig. 2 show the change in microstructure of rapidly solidified Ti-rich Ti–Ni alloy fibers with respect to Ti content. Observation was carried out in back-scattered electron (BSE) mode since the BSE image efficiently distinguishes different phase. Because of the contact of the melt with the quenching wheel during high speed casting of melt overflow system, the heat would be extracted to the direction of the wheel during solidification, so that the fibers consisted of long columnar grains crystallographically oriented with their columnar directions normal to the surface, which were the reverse direction of the heat-extraction. Then the all alloy fibers show cellular morphology as shown in Fig. 2(a)–(d).

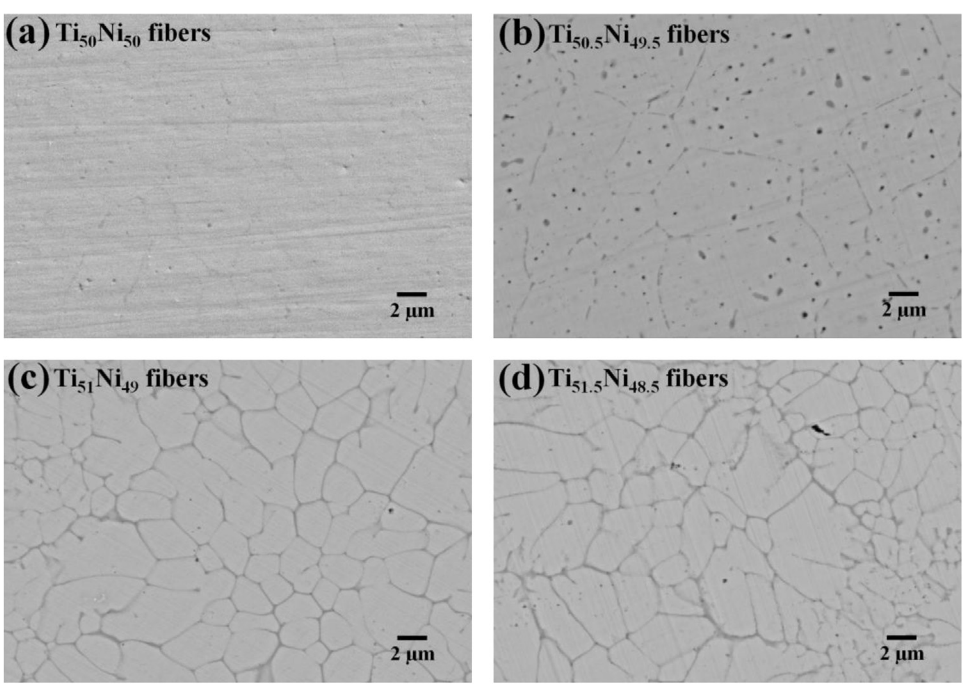

Fig. 2. (a–d) Back scattered SEM images of section parallel to the surface of the rapidly solidified fibers.