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Compressive property of porous NiTi alloy synthesized by combustion synthesis

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Abstract

Porous NiTi shape memory alloy (SMA) is a promising biomedical material applied as a human implant. Compressive properties of porous NiTi SMAs fabricated by combustion synthesis were investigated in this paper by compression tests. The results indicated that the nominal ultimate compressive strength and strain of porous NiTi SMAs were dependent on porosity and independent on strain rate. The compressive strength of porous NiTi SMA met the basic strength demand of human cancellous bone with corresponding porosity.

Keywords: Mechanical properties; Shape memory alloy; Combustion synthesis; Porous material; Porosity

1. Introduction

In the world, many patients need replacement and reparation of human bone tissues such as bones and dental roots due to disease or congenital deficiency. It becomes an urgent task to fabricate implant biomaterials to release the pains of patients [1].

Some natural biomaterials, such as cancellous bones, have inevitably porous structure with very high strength-to-weight ratio [1–4]. Porous materials consisting of individual struts connected in a three-dimensional array are favorable candidates for human implants. Among some kinds of biomaterials, porous ceramics such as hydroxyapatite are relatively weak owing to their brittle nature although they have ingredients similar to human bone [1]. Porous NiTi SMA has attracted great concern owing to its special superelasticity, good biocompatibility, unique porous structure, etc. [5–19]. Porous biomaterial with a pore size of 100~500 μm can allow human tissue ingrowth and body fluid transmission. Mechanical properties and porosity of porous NiTi SMA can be controlled to meet the different requirements by means of adjusting fabrication parameters. Porous NiTi SMA has been applied successfully in medical fields such as biomedical implant (e.g. orthopedics, traumatology, vertebrarium, maxillofacial surgery and so on), also it has been used as a medical instrument such as cryogenous applicator in Russia [5,6]. The application field of porous NiTi SMA is expanding now.

For biomaterials, mechanical compatibility is an important aspect of biocompatibility. Usually, the poor mechanical compatibility of biomaterials used currently is the mismatch of material rigidity with host tissues. This defect would cause stress–shielding effect, as an implanted material of high rigidity carries most of the applied stress. As a result, osteoporosis of the surrounding bone can occur. But, for most of traditional solid metallic biomaterials such as titanium alloys, Co–Cr alloys and stainless steels, their mechanical strength and elastic moduli are much higher than that of human bone tissues. So bone tissue implant candidate with appropriate mechanical property comparable to human bone tissue has become the research focus of the biomaterial field [1,20,21].

There are some reports on preparation and biocompatibility [5–19], but there is few systematic literature about compressive property of porous NiTi SMA. Considering that implants typically undergo compressive stress, it is the motivation of this paper to study compressive properties of porous equiatomic NiTi SMAs prepared from combustion synthesis.

2. Experimental

Usually, porous NiTi SMA can be prepared from

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traditional powder sintering and novel combustion synthesis. Combustion synthesis, also called self-propagating high-temperature synthesis is superior to powder sintering with advantages of saving time, saving energy, pure product and so on [6,22]. In this paper, combustion synthesis was chosen to synthesize porous NiTi SMA. During synthesis process, pure elemental titanium (≤74 μm) and nickel (≤38 μm) powders were mixed according to equiatomic ratio, then the blended powders were made into rod-shaped compact pellets. The preheating temperature during combustion synthesis process was controlled between 523 and 723 K. The preheated compact was ignited at one end by tungsten coil in a furnace under the protection of pure argon with pressure of 2.5×10^5 Pa. Once ignited, combustion wave could self-propagate along the axis to the other end of the compact in a very short time, then porous NiTi SMA was synthesized.

In this paper, compressive properties of equiatomic porous NiTi SMAs with different porosity were studied by uniaxial compression tests at strain rate of 10^{-3} s^{-1}. The compressive samples were cut in a size of Φ 9×12.5 mm^2 from rod-shaped porous NiTi SMAs along longitudinal direction. The nominal stress–strain curve was recorded. The ultimate compressive strength and compressive strain were defined as the values of stress and strain, respectively, at which stress reached the maximum value in the stress–strain curve.

Compressive tests at different strain rates (10^{-3}, 10^{-2} and 10^{-1} s^{-1}, respectively) were carried out to investigate the correlation between compressive property of porous NiTi SMA and strain rate during compressive test.

Scanning electron microscopy (SEM) was performed to study pore morphology and compressive fracture morphology of porous NiTi SMA.

3. Results and discussion

As shown in Fig. 1, porous NiTi SMA prepared from combustion synthesis possessed characteristics of three-dimensionally intercommunicated permeable and open pore structure. Average pore size of porous NiTi SMA with porosity between 49 and 65% studied in this paper was between 120 and 600 μm. Pore size distribution was ranged mainly between 200 and 600 μm, increasing with the increase of porosity. The pore size parameters met the basic pore size demand of porous biomaterial used for cancellous bone implant [6,7]. According to Refs. [2,3], the configuration of open cell cellular material could be modeled as connected network of rods forming open cells.

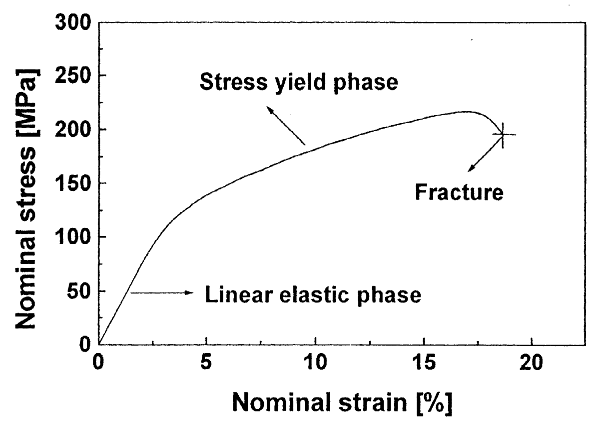

Fig. 2. Stress–strain curve of porous NiTi SMA with porosity of 54.2% in compression.

The compressive stress–strain curve of porous NiTi SMA with porosity of 54.2% was presented in Fig. 2. The curve had three distinct portions: an apparent linear elastic phase in which cell walls would bend or be compressed elastically, an increasing steeply stress yield phase in which cells would collapse by buckling and plastic yielding, then the stress attained the maximum followed by fracture failure. In the last phase, cell walls would meet and be compressed. Pores would participate in the whole deformation process.

The schematic stress–strain curve of cancellous bone in compression was presented in Fig. 3, it also had three portions: a linear elastic portion, an apparent plateau of almost constant stress and the final densification phase [2]. It could be seen that the mechanical behavior of cancellous bone was very different from that of porous NiTi SMA,

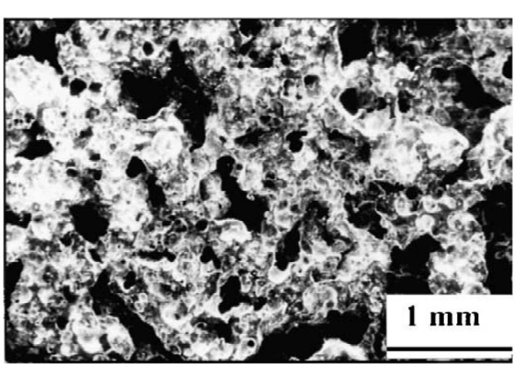

Fig. 1. SEM image of pore morphology for porous NiTi SMA.

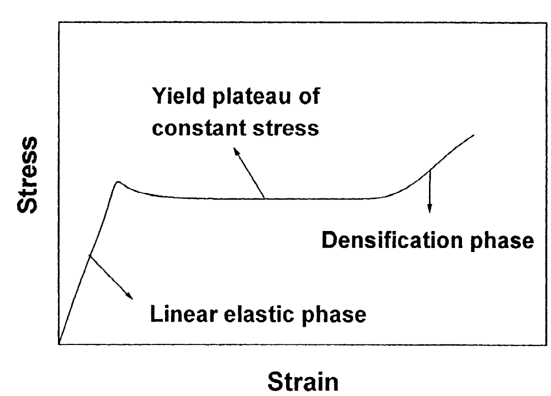

Fig. 3. Schematic stress–strain curve of cancellous bone in compression.

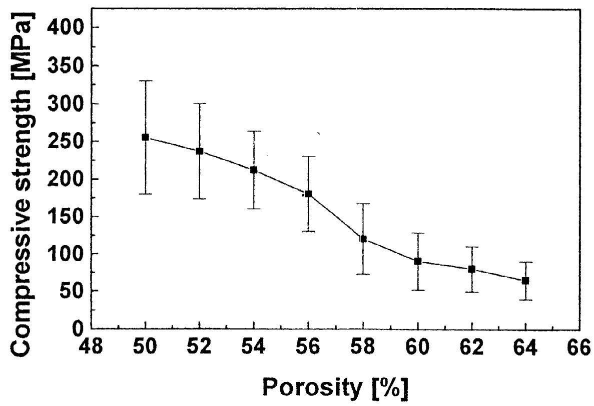

Fig. 4. Dependence of ultimate compressive strength on porosity of porous NiTi SMA.

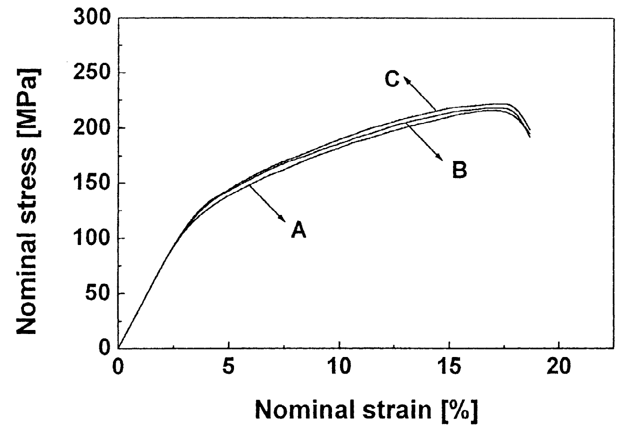

Fig. 6. Correlation between compressive stress–strain curve of porous NiTi SMA (with porosity of 54.2%) and strain rate (A—10^{-3} s^{-1}, B—10^{-2} s^{-1}, C—10^{-1} s^{-1}).

especially in the second phase. The participation of martensites in porous NiTi SMA may result in the rapid increase of stress with the increase of deformation.

Nominal ultimate compressive strength of porous NiTi SMA with different porosity was shown in Fig. 4. It could be seen clearly that compressive strength decreased dramatically with increasing porosity of porous NiTi SMA. Compressive strength range of cancellous bone was 1–100 MPa [1,2]. The compressive strength of porous NiTi SMA met the basic mechanical demand of cancellous bone with the different corresponding porosity.

Nominal ultimate compressive strain of porous NiTi SMA with different porosity was shown in Fig. 5. It should be pointed out that the porosity values of 50, 52, 54, 56, 58, 60, 62 and 64% in Figs. 4 and 5 were average values with deviation of ±1%, respectively. It could be seen that compressive strain decreased remarkably with increasing porosity of porous NiTi SMA. The load-bearing area of porous NiTi SMA sample would decrease with the increasing porosity due to increase of pores, contributing to decrease of compressive strength and compressive strain.

The correlation between stress–strain curve of porous NiTi SMA and strain rate during compression was presented in Fig. 6. It could be shown clearly that the strain rate had little effect on compressive stress–strain curve of porous NiTi SMA. It should be noted that strain rate had remarkable influence on stress–strain behavior of some open-porous metals and solid monolithic NiTi SMA. The stress–strain curve of cancellous bone was dependent on strain rate, different from that of porous NiTi SMA. The compressive strength of cancellous bone was a function of the imposed strain rate [1,23].

Compressive fracture morphology was shown in Fig. 7, it could be seen that there were some ductile dimples (A in Fig. 7), indicating it had ductile fracture characteristics, regardless of strain rate. It could be seen there were some original pores (B in Fig. 7) that may participate in the deformation process.

It should be pointed out that Young's modulus, which was also important for the design of biomaterial, would be reported elsewhere.

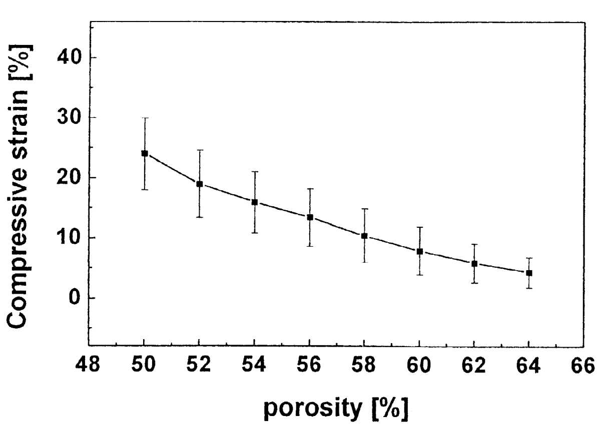

Fig. 5. Dependence of ultimate compressive strain on porosity of porous NiTi SMA.

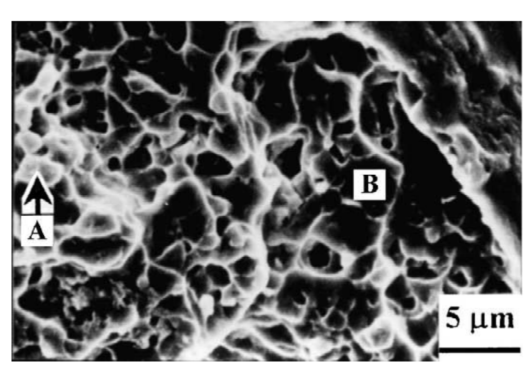

Fig. 7. SEM image of compressive fracture morphology for porous NiTi SMA.

4. Conclusions

1. Porous NiTi SMA fabricated by combustion synthesis had permeable porous structure of three-dimensionally interconnected. Pore size parameters met the basic pore size requirement of cancellous bone implant.
2. Both ultimate compressive strength and compressive strain decreased with increasing porosity of porous NiTi SMA.
3. Compressive stress–strain curve of porous NiTi SMA was independent on strain rate during compression test.
4. Compressive fracture morphology of porous NiTi SMA had ductile fracture feature.
5. The compressive strength of porous NiTi SMA met the strength requirement of human cancellous bone with corresponding porosity.

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