Journal of Alloys and Compounds 731 (2018) 569–576

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Mechanical response of near-equiatomic NiTi alloy at dynamic high pressure and strain rate

Xuping Zhang [a], Guiji Wang [a, *], Binqiang Luo [a], Simon N. Bland [b], Fuli Tan [a], Feng Zhao [c], Jianheng Zhao [a, **], Chengwei Sun [a], Cangli Liu [d]

[a] Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang 621999, China
[b] Imperial College London, Blackett Laboratory, London sw7 2az, United Kingdom
[c] The Peac Institute of Multiscale Sciences, Chengdu 610031, China
[d] China Academy of Engineering Physics, Mianyang 621999, China

ARTICLE INFO

Article history:
Received 10 August 2017
Received in revised form
9 October 2017
Accepted 10 October 2017
Available online 12 October 2017

Keywords:
NiTi alloy
Equation of state
Constitutive relationship
Quasi-isentropic compression
Shock compression

ABSTRACT

Understanding the behavior of near equi-atomic NiTi alloys under high strain rates and high pressures is important for the development of shock mitigating structures, particularly those that protect satellite and space vehicles from the impact of hyper velocity space debris. In this paper, the equation of state and constitutive relationships of NiTi alloy at pressures of 20–50 GPa and strain rates from $10^4 s^{-1}$ to $10^7 s^{-1}$ were investigated by means of magnetically driven quasi-isentropic compression and by shock compression from the impact of magnetically launched flyer plates. An inflection point at a pressure of 2–3 GPa was found on plots of Lagrangian sound speed versus particle velocity in both quasi-isentropic and shock compression experiments, and it shows the elastic-plastic transition of austenitic NiTi alloy. The effect of the strain rate on the elastic limit of NiTi alloy was clearly seen between strain rates of $10^4 s^{-1}$ and $10^7 s^{-1}$. We also found that the bulk sound speed calculated from the shock data was lower than that deduced from the ultrasonic measurements. Finally, a rate dependent Johnson–Cook model was modified to describe the dynamic responses of NiTi. With this modified model, hydrodynamic simulations agreed well with our observations.

1. Introduction

Due to its properties including pseudo-elasticity, resilience to deformation, resistance to corrosion and biocompatibility, let alone its shape memory characteristics, binary polycrystalline NiTi alloy has been studied extensively and is widely used in industrial applications [1–3]. For example, NiTi alloy is used in aeronautical actuators, the protection structures in seismic test equipment and in satellites and space vehicles for protection against space debris that may be travelling at velocities >7 kms^{-1}. In order to provide optimized designs for spacecraft it is crucial to investigate the mechanical responses and obtain equation of state data for NiTi alloy under high strain rates and high pressures [2–4]. It is also known that U-Nb, an important alloy for advanced nuclear applications, has similar plastic deformation mechanisms and shape memory characteristics to NiTi alloy. Hence experiments with NiTi can help predict the properties of U-Nb, and can be used to perfect experimental techniques safely before carrying out studies on this potentially hazardous material [5–7].

Several techniques have been used to study the dynamic behavior of NiTi alloy at different strain rates and pressures. Split Hopkinson Pressure Bar (SHPB) measurements have provided data at intermediate strain rates from ~10^2 s^{-1} to 10^4 s^{-1}. In SHPB experiments, W. W. Chen [8], S. N. Nasser [9,10], W. G. Guo [11], Y. Qiu [12] used a pulse-shaping technique to control the strain rates and studied the stress-induced martensitic transition mechanism. They pointed out that the onset of stress induced martensitic transitions increased with increasing strain rates. Results by S. N. Nasser and W. G. Guo showed that a critical strain rate of ~6000s^{-1} existed for stress-induced martensite formation, beyond which no transitions occurred [9–11].

In shock loading experiments at higher strain rates, however, there is some disagreement on whether or not a stress induced

* Corresponding author.
** Corresponding author.
E-mail addresses: wangguiji@126.com (G. Wang), jianh_zhao@sina.com (J. Zhao).

https://doi.org/10.1016/j.jallcom.2017.10.080
0925-8388/© 2017 Published by Elsevier B.V.

martensitic transition occurs and what the effects of strain rate on this transition are. In 1996, the phase transition and microstructure of two compositions of NiTi alloy under shock loading were investigated by A. M. Thakur [13]. Thakur thought that the martensitic transformation resulted from the tensile pulse and not from the compressive stress. In 2002–2006, Hugoniot data at stress levels up to 15 GPa were obtained by J. C. F. Millett and Y. J. E. Meziere with a single stage gas gun [14–16]. This indicated two different linear relationships between the shock wave velocity and particle velocity with an inflection point between them occurring at pressures of ~4.8 GPa. They attributed this inflection to the stress-induced martensitic phase transformation. In shock experiments conducted by R. E. Hackenberg [17,18] and Y. B. Guo [19], though, it was argued that an elastic precursor could be responsible for the inflexion point, and the pressure at which this occurred was 2.5 GPa. Recently, S. V. Razorenov [20] studied the dynamic elastic limit of NiTi in regions of single phase specimens. His results showed that the elastic limit of the austenite and martensite phases were 2.8 GPa and 0.3 GPa respectively, supporting the suggestion that an inflexion at 2.5 GPa could be due to elastic-plastic transitions. There are some more recent reports on martensitic transformation of NiTi under shock loading [21,22], however it is unclear if there could be other reasons to for the Martensitic transformation here.

In all, there is little data available that focuses on the equation of state of NiTi alloy above 15 GPa and data in the 2–5 GPa region – which is critical in determining whether stress induced Martensitic transformations are occurring – is sparse at strain rates above $10^4 s^{-1}$. The objectives of this paper is to clarify the effect strain rate effect on any stress-induced phase transitions of NiTi above $10^4 s^{-1}$ and to obtain constitutive relations and equation of state data on NiTi by means of the magnetically driven quasi-isentropic compression experiments and magnetically driven flyer plate impact experiments. The findings in this work will be a basis for validating the materials models and hydrodynamic simulations, enabling better structures for the industrial applications.

2. Materials and experimental techniques

2.1. Materials characteristics

The near–equiatomic NiTi alloys are provided by Chinese Northwestern SMA Incorporation and S. N. Bland at Imperial College London. Material property data for the NiTi alloys studied in this investigation are presented in Table 1. The acoustic properties were measured using a pulse receiver with quartz transducers at a frequency of 5 MHz. The starting(s) and finishing(f) phase transformation temperatures for the martensite and austenite phase were obtained by Differential Scanning Calorimetry (DSC) and are $M_s = -14.6$ °C, $M_f = -19.7$ °C, $A_s = -11.4$ °C, $A_f = -0.7$ °C. X-ray diffraction (XRD) analysis indicated that the crystal lattice structures of NiTi was body-centered cubic (B2). Microstructure of the as-received NiTi alloy was obtained by electron backscattering diffraction (EBSD). Fig. 1 shows a grain orientation map of the NiTi alloy sample used in our experiments. The microstructure appears to be homogeneous with an average grain size of about 35 μm.

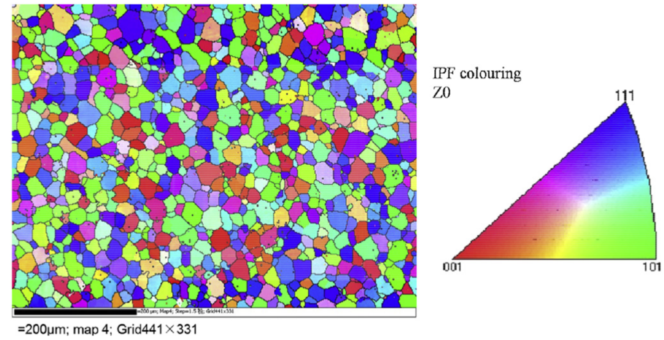

Fig. 1. Microstructure and inverse polo figure (IPF) of NiTi alloy used in the work, measured by EBSD. The scanning step size is 2 μm. And in the EBSD measurements the indexing quality, which is estimated through confidence index of the samples, is high for almost 90% of the scan.

2.2. Experimental techniques and conditions

A series of quasi-isentropic compression and planar shock wave experiments were performed on pulsed power generator CQ-4, which can deliver pulsed currents with peak values of 3~4 MA and rise time of 470 ns–600 ns to short circuit loads. Using optimally shaped electrode panels, ramp wave pressures up to ~100 GPa can be produced in copper and higher impedance metals on CQ-4. Alternately using the magnetic pressure to launch aluminium flyer plates can produce velocities >15 km s^{-1} [23,24].

Due to the relatively long rise times over which pressure increases in the quasi-isentropic compression experiments, the stress wave structure travelling through a target can be clearly observed through velocimetry measurements. In addition, controlled the rise time of the current pulse alters the strain rate, readily enabling experiments in a regime of 10^4-10^6 s^{-1}. A schematic of the experiment is shown in Fig. 2. The shaped electrode panels ensure that the magnetic field is uniformly distributed across the loading surface, and that pressure propagates as a near planar wave through the thickness of panels [23,24]. The dependence of the pressure loading with time can be calculated by measuring the velocity of an electrode panel through an impedance matched window (PIN3 in Fig. 2) and applying a backwards integration method [23]. This and other

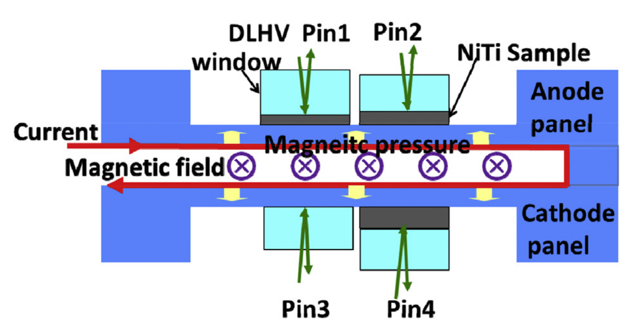

Fig. 2. Schematic diagram of magnetically driven quasi-isentropic compression experiments. There are four DLHV probes in one shot, three to measure the interface particle velocities between different thickness samples and windows and one to measure the interface particle velocities between electrode panel and windows.

Table 1
Characteristics of as-received NiTi alloy. 'C_{LO}' denotes longitudinal sound speed, 'C_s' denotes shear sound speed, 'C_b' denotes bulk sound speed. 'ν' denotes Poisson's ratio. 'M_s' denotes starting phase transformation temperatures for the martensite, 'M_f' denotes finishing phase transformation temperatures for the martensite, 'A_s' denotes starting phase transformation temperatures for the austenite, 'A_f' denotes finishing phase transformation temperatures for the austenite.

density (g/cm^3)	composition	C_{LO} (kms^{-1})	C_s (kms^{-1})	C_b (kms^{-1})	ν	M_s (°C)	M_f (°C)	A_s (°C)	A_f (°C)
6.42	$Ti_{46-48}Ni_{52}$	5.434	1.775	5.032	0.436	−14.6	−19.7	−11.4	−0.7