Materials Research Bulletin 58 (2014) 234–238

Contents lists available at ScienceDirect

Materials Research Bulletin

journal homepage: www.elsevier.com/locate/matresbu

Hot forging design of as-cast NiTi shape memory alloy

Jong-Taek Yeom [a], Jeoung Han Kim [a,d,*], Jae-Keun Hong [a], Seong Woong Kim [a], Chan-Hee Park [a], Tae Hyun Nam [b], Kee-Young Lee [c]

[a] Titanium Department, Korea Institute of Materials Science (KIMS), 797 Changwondaero, Seongsan-gu, Changwon 641-831, South Korea
[b] School of Materials Science and Engineering & ERI, Gyeongsang National University, 900 Gazwadong, Jinju, Gyeongnam 660-701, South Korea
[c] KPC M Corporation, 115 Deokchon-ri, Wachon-myeon, Gyeongsan, Gyeongbuk 712-843, South Korea
[d] Department of Advanced Materials Engineering, Hanbat National University, Daejeon 305-719, South Korea

ARTICLE INFO

Article history:
Available online 26 April 2014

Keywords:
A. Alloys
A. Intermetallic compounds
B. Intercalation reactions
B. Mechanical properties
C. Electron microscopy
D. Fracture

ABSTRACT

A hot forging process of an as-cast NiTi shape memory alloy was designed by processing maps and a finite element method analysis. The NiTi alloy samples used in this study were made using a vacuum plasma arc melting process. In order to analyze the microstructural change and flow behavior of the as-cast NiTi alloy during the ingot breakdown process, high temperature compression tests were carried out at different temperatures and strain rates up to a true strain level of 0.9. Deformation processing maps were generated by using the dynamic materials model approach developed by Prasad to search for the optimum hot forging process conditions. The flow instability criterion proposed by Ziegler was utilized to evaluate the unstable deformation region in the processing map. The grain refinement was achieved by recrystallization during high temperature deformation of the NiTi alloy. Finally, the optimum hot forging design to obtain a sound NiTi billet without forging defects was identified with the actual ingot breakdown process.

1. Introduction

Ingot breakdown is the most important process for achieving good-quality wrought materials. The ingot breakdown of NiTi shape memory alloys is mainly achieved by hot working processes such as forging, rolling, cogging, and etc. In previous studies, most hot workability analyses for NiTi shape memory alloys have focused on NiTi alloy ingot prepared by vacuum induction melter. Dehghani and Khamei [1,2] studied the hot deformation behavior of a Ti-60.0 wt.% Ni alloy by a hot compression test carried out at temperatures ranging from 950 to 1050 °C and at strain rates of 0.001–0.35 s^{-1}. They reported that this alloy underwent dynamic recrystallization. Morakabati et al. [3] studied the hot workability of a wrought Ti-55 wt.% Ni alloy and suggested that dynamic recovery is the dominant restoration phenomenon during hot working of this alloy. On the other hand, researches on the hot workability of as-cast NiTi alloys manufactured by a melting process using water cooled Cu crucible techniques such as vacuum induction skull melting (ISM) and plasma arc melting (PAM) are very limited. In the present research, optimum conditions of hot forging for a plasma arc melted NiTi alloy were established and processing maps of a NiTi alloy were generated based on a quantitative understanding of the dynamic deformation behavior.

2. Experimental procedure

The material used in this work was as-cast Ti-55.5 wt.% Ni alloy samples (Φ65.0 mm × 13.0 mm) prepared by a plasma arc melting (PAM) process. In order to analyze the high temperature deformation behavior of the material with state variables such as strain, strain rate, and temperature, hot compression tests were performed at temperatures ranging from 800 to 1100 °C with 50 °C intervals and at strain rates ranging from 10^{-2} to 10 s^{-1}. Compression test specimens of 12 mm height and 8 mm diameter were machined. All the tests were carried out under vacuum (~10^{-2} Torr) up to a strain level of approximately 0.9 using a GLEEBLE-3800 testing machine. The flow stress curves obtained from compression tests were corrected for deformation heating effects based on the following expression [4]:

$$\Delta T = \frac{\alpha \int_0^{\bar{\varepsilon}} \bar{\sigma}\, d\bar{\varepsilon}}{C_p \rho} \quad (1)$$

where α is the fraction of plastic work converted to heat, taken here to be 0.9. ρ is the density, $\bar{\sigma}$ is the effective stress, $\bar{\varepsilon}$ is the effective strain, and C_p is the heat capacity of the target material.

* Corresponding author at: Department of Advanced Materials Engineering, Hanbat National University, Daejeon 305-719, South Korea. Tel.: +82 42 821 1240; fax: +82 42 821 1592.
E-mail addresses: kimjh000@gmail.com, jh.kim@hanbat.ac.kr (J.H. Kim).

http://dx.doi.org/10.1016/j.materresbull.2014.04.049
0025-5408/

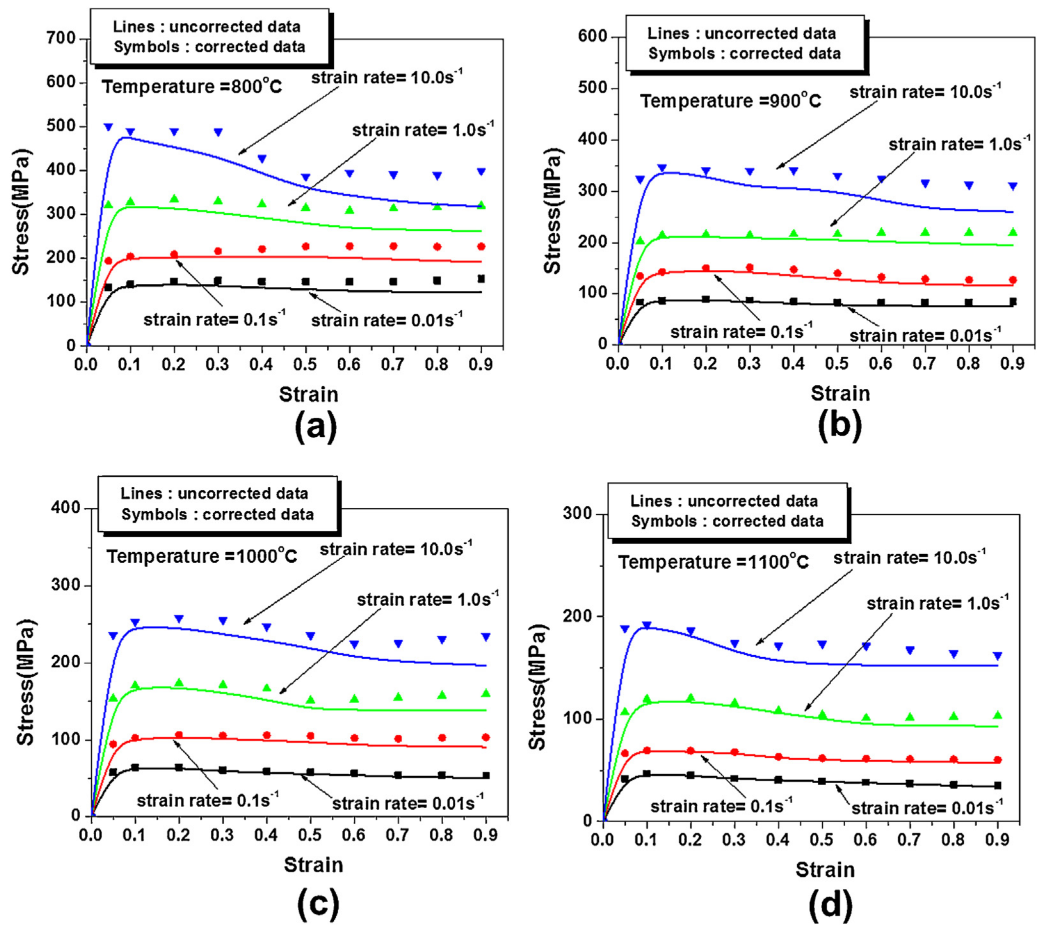

Fig. 1. True stress-versus-strain curves before and after adiabatic heating correction.

The flow curves are then plotted against $T_0 + \Delta T$, where T_0 is the nominal test temperature. The isothermal flow stress data can be obtained by interpolating these plots [5]. Finally, the corrected flow curve data were used to generate the deformation processing map of the NiTi material.

3. Results and discussion

3.1. Method for evaluating hot workability of as-cast Ti-55.5 wt.% Ni alloy

The dynamic materials model (DMM) [6–8] was developed on the basis of the fundamental principles of continuum mechanics of large plastic flow, physical systems modeling, and irreversible thermodynamics. The DMM includes an important dimensionless parameter called the efficiency of power dissipation. The parameter η indicates the dissipating ability of the workpiece as normalized by the total power absorbed by the system. For an ideal linear dissipater, strain rate sensitivity $m = 1$ and $\eta = 1$ [9].

$$\eta = \frac{2m}{m+1}, \qquad m = \left(\frac{\partial \log\sigma}{\partial \log\dot{\varepsilon}}\right)_{T,\varepsilon} \tag{2}$$

where σ is the stress and $\dot{\varepsilon}$ is the strain rate. However, the DMM has a limitation in expressing unstable conditions. In order to overcome this limitation, the DMM was coupled with an instability criterion developed by Ziegler [10]. According to Ziegler's criterion, deformation will be unstable when a dimensionless instability parameter ξ becomes negative, as shown in Eq. (3).

$$\xi = \frac{\partial \ln(m/(m+1))}{\partial \ln\dot{\varepsilon}} + m < 0 \tag{3}$$

3.2. Flow stress curves and deformation process map

Fig. 1 shows a comparison of the corrected stress-versus-strain curve and the raw data obtained from hot compression tests of the

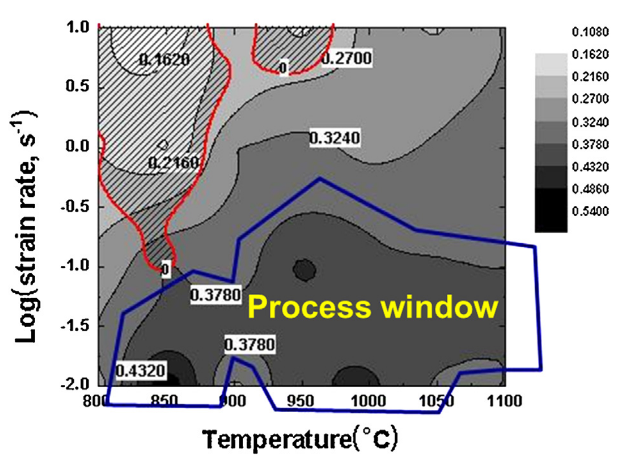

Fig. 2. Deformation processing map of Ti-55.5 wt.% Ni alloy at a strain of 0.9.