Transactions of the Materials Research Society of Japan 29[7] 3009-3012 (2004)

Mechanical and Shape Memory Properties of Ti-Sc-Mo Biomedical Alloys

Takashi Maeshima[1], Kiyoshi Yamauchi[2], Uchiyama Hiroaki[2] and Minoru Nishida[3]
[1] Guraduate School of Science and Technology, Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan
Fax: 81-96-342-3710, e-mail: 029d8116@gsst.stud.kumamoto-u.ac.jp
[2] NEC Tokin Co., Ltd., Sendai 982-0003, Japan
[3] Department of Materials Science and Mechanical Engineering, Kumamoto University, 2-39-1 Kurokami,
Kumamoto 860-8555, Japan
Fax: 81-96-342-4710, e-mail: nishida@gpo.kumamoto-u.ac.jp

Mechanical and shape memory properties of Ti-Sc-Mo alloys are investigated. Some of selected compositions in Ti-Sc-Mo alloys demonstrate superior shape recovery more than 5% of surface strain with heating after bending test. Microstructure observation before and after tensile deformation shows that the shape memory effect is associated with stress induced $\beta \rightarrow \alpha''$ martensitic transformation. Vickers hardness and 0.2% proof stress are remarkably decreased and elongation is increased with Sc content. The remarkable grain refining is also achieved. The relation between microstructure and shape memory behavior, mechanical properties is briefly discussed.

Keywords: biomaterial, shape memory alloy, titanium-scandium-molybdenum alloy, martensitic transformation

1. INTRODUCTION

Since Ti-Ni alloys exhibit superior shape memory properties and superelasticity, they have been used for medical tool such as orthodontic wire, teeth-root prosthesis, stent in blood vessels [1]. However, the Ti-Ni alloys contain Ni atoms which are strongly concerned about allergenic and carcinogenic to the human body. Thus the development of Ni-free titanium shape memory alloys is required to substitute for Ti-Ni alloys. One of the candidate materials is metastable β-titanium alloys which are designed with appropriate combination of α and β stabilized elements [2-4]. In order to create new β-titanium alloy for biomedical applications, we pay attention to Sc and Mo as α stabilized and β stabilized element, respectively. The purpose of the present study is to report mechanical and shape memory properties of newly developed Ti-Sc-Mo biomedical alloys.

2. EXPERIMENTAL PROCEDURE

The chemical compositions of alloys investigated were chosen to be 1, 3, 5 and 7mol%Sc and 6mol%Mo. These were prepared by arc melting in an Ar atmosphere. Weight changes before and after arc melting were negligibly small in all the alloys. The ingots were homogenized at 1373K for 86.4ks in vacuum and then hot and cold rolled into 0.5mm in thickness. Specimens were prepared by electro-discharge machining from the rolled plates, encapsulated in an evacuated quartz tube under the vacuum of less than 5×10^{-3} Pa, solution-treated at 1273K for 1.8ks followed by quenching into iced water by breaking tube. Shape memory properties were evaluated with convenient bending test. The bending test was carried out at room temperature where the specimen was deformed into a round shape and heated up about 550K. Mechanical properties were evaluated with Vickers hardness measurement and tensile test. Vickers hardness was measured by using applied load of 200g and loading time of 10s. HV values employed were averaged at least 5 points excluding the lowest and highest values. Tensile tests were performed at room temperature under the strain rate of 4.16×10^{-4}/s. Cyclic tensile and heating tests were also performed to determine the shape recovery strain quantitatively. The constituted phases of before and after tensile deformation were detected by the X-ray diffraction (XRD) and optical microscopy.

3. RESULTS AND DISCUSSION

Fig. 1 shows results of convenient bending test of Ti-6Mo and Ti-5Sc-6Mo alloys. Shape memory effect is observed by heating after deformation in both alloys. It is clearly seen that the shape memory effect in Ti-5Sc-6Mo alloy is superior to that in Ti-6Mo alloy. Sc content dependence of shape memory behavior in Ti-Sc-Mo alloy is summarized in Fig. 2. Recovery ratio R_{sme} with shape memory effect is defined as follows;

$$R_{sme}=(\varepsilon_s-\varepsilon_r)/\varepsilon_s\times100 \qquad (1)$$

where ε_s: surface strain after bending deformation and ε_r: residual surface strain after heating as presented in Fig.1 (b) and (c), respectively. In addition to the R_{sme}, recovery ratio R_{sb} with spring back after bending deformation is

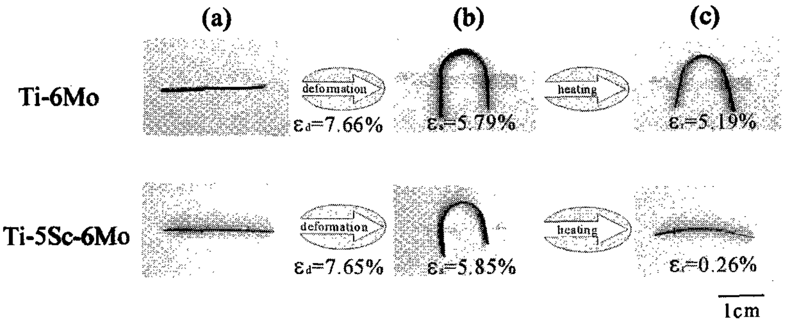

Fig. 1 Results of convenient bending and shape recovery test in Ti-6Mo and Ti-5Sc-6Mo alloys.

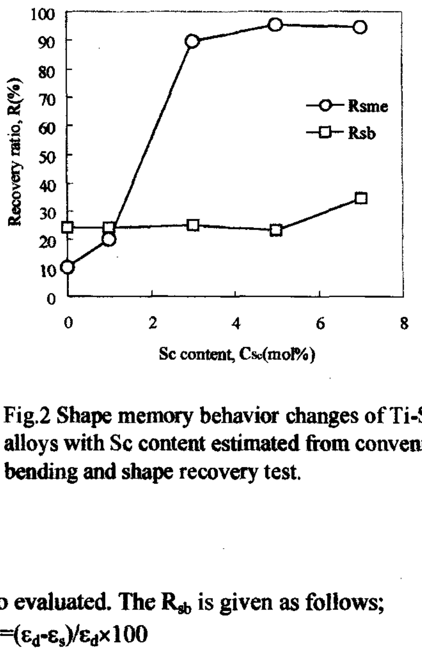

Fig.2 Shape memory behavior changes of Ti-Sc-Mo alloys with Sc content estimated from convenient bending and shape recovery test.

also evaluated. The R_{sb} is given as follows;

$$R_{sb}=(\varepsilon_d-\varepsilon_s)/\varepsilon_d\times 100 \qquad (2)$$

where ε_d: applied surface strain with bending deformation as presented in Fig. 1 (a). The R_{sb} is considered to be a recovery property partially related to superelasticity. R_{sme} increases with increasing Sc content up to 3mol% and keep constant about 95% at 5 to 7 mol%Sc. The R_{sb} keep constant about 25% up to 5mol%Sc and then increases in 7mol%Sc. From these results, best composition for the shape memory effect is determined to be Ti-5Sc-6Mo alloy. Since R_{sb} is increased in Ti-7Sc-6Mo alloy, the development of superelastic property at room temperature can be expected with structure control through the aging, thermo mechanical treatment and so on [4]. This is now under study.

Fig. 3 shows stress-strain curves measured through cyclic tensile deformation of Ti-5Sc-6Mo alloys. Broken arrows in the bottom of figure indicate the shape recovery strain with heating. The specimen was deformed to 5% strain at the first cycle. Then the shape recovery strain is 4.8%. At the 2nd cycle, the specimen was deformed to 3.4% and the recovery is nearly perfect. The recovery strain is 5.3% at the third cycle. The constant recovery strain about 5% was obtained after several cycles. These results demonstrate that the developed Ti-5Sc-6Mo alloy posses excellent shape memory effect.

Fig. 4 (a) and (b) show Vickers hardness, 0.2% proof stress and elongation changes with Sc content in the alloys, respectively. HV value decreases drastically with only 1mol% Sc addition and keeps constant around HV230 regardless of Sc content. Correspondingly, 0.2% proof stress decreases with increasing Sc content. Both minimum values are obtained in Ti-5Sc-6Mo alloy. Tensile elongation remarkably increases about 35% with increasing Sc content from 3 to 5 mol%. However, the elongation decreases in Ti-7Sc-6Mo alloy. The origin of mechanical property changes is discussed later.

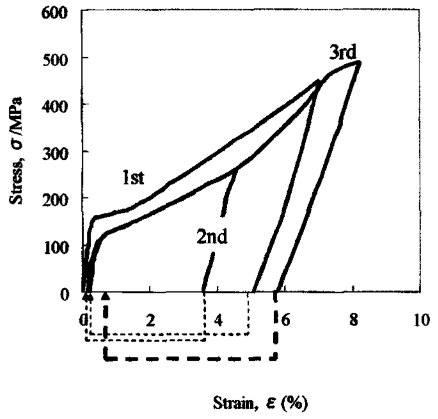

Fig. 3 Stress-strain curves of cyclic tensile deformation and recovery strain in Ti-5Sc-6Mo alloy.

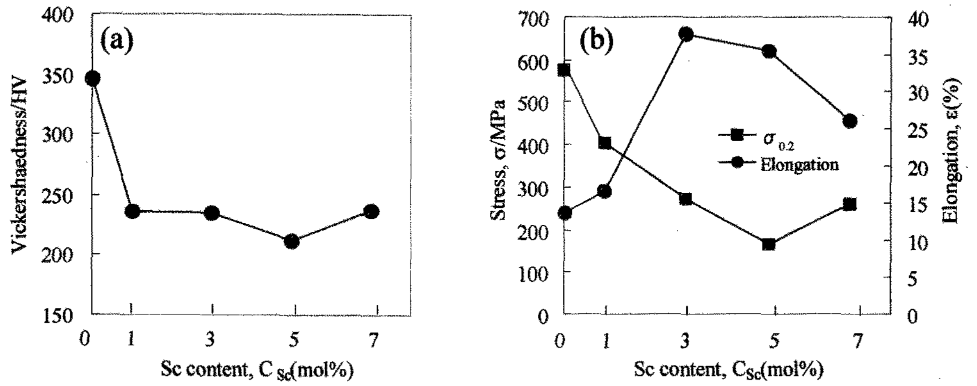

Fig. 4 (a) Vickers hardness and (b) 0.2% proof stress and elongation changes of Ti-Sc-6Mo alloys with Sc content.

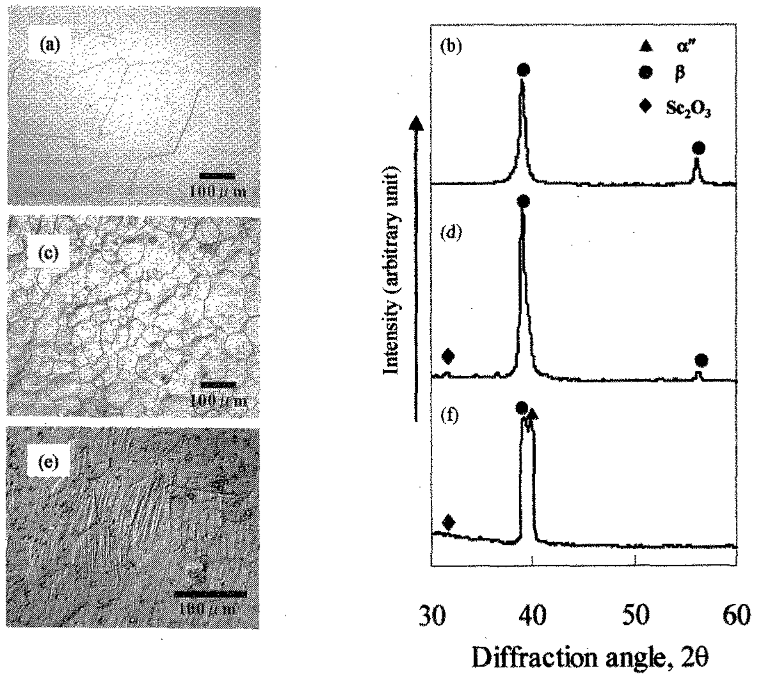

Fig. 5 (a), (c) and (e) Optical micrograph, and (b), (d) and (f) XRD profiles in Ti-6Mo and Ti-5Sc-6Mo alloys. (a) and (b) in Ti-6Mo. (c) and (d) before and, (e) and (f) after tensile deformation with 4% strain in Ti-5Sc-6Mo.

Microstructure and XRD profile in Ti-6Mo are shown in Fig. 5 (a) and (b), respectively. Those in Ti-5Sc-6Mo before tensile deformation are shown in Fig. 5 (c) and (d), respectively. Grain size of Ti-6Mo is about 270μm and that of Ti-5Sc-6Mo is about 25μm as clearly recognized from (a) and (c). XRD results in (b) and (d) suggest that both the alloys consist of β phase. In Ti-5Sc-6Mo, Sc oxide is also detected, which may correspond to dispersed small particles in (c). The marked grain refining is probably achieved by grain boundary pinning effect of Sc oxide. After the deformation with 4% strain, banded surface relief of α'' martensitic phase appears as shown in Fig. 5 (e). This is confirmed by XRD profiles in Fig. 5 (f) in which the intensity of β phase decreases and that of α'' phase increases. It is clear that the shape memory effect in Ti-Sc-Mo alloy is associated with the stress induced β to α'' martensitic transformation. From these results, relation between microstructure and mechanical properties presented in Fig. 4 are summarized as follows. The remarkable increment of elongation in Ti-3Sc-6Mo and Ti-5Sc-6Mo alloys is attributable to the grain refining. However, in spite of the grain refining, hardness and

0.2% proof stress decrease remarkably in Ti-3Sc-6Mo and Ti-5Sc-6Mo. It is likely that the solution strengthening of Ti matrix with oxygen is decreased due to the formation of Sc oxide, which is considered to be a kind of scavenging effect.

4. SUMMARY

In order to develop the biomedical Ni-free β-titanium shape memory alloys substituting for Ti-Ni alloys, mechanical and shape memory properties of Ti-Sc-Mo alloys were investigated. Ti-3Sc-6Mo, Ti-5Sc-6Mo and Ti-7Sc-6Mo alloys exhibit superior shape recovery ratio more than 90% in convenient bending and heating test. The constant recovery strain about 5% was obtained in Ti-5Sc-6Mo alloy with tensile deformation and heating cycles. Vickers hardness and 0.2% proof stress are remarkably decreased and elongation is increased with Sc content up to 5mol% Sc. The former is attributable to the decrease of solution strengthening in Ti matrix with oxygen due to the formation of Sc oxide. The latter is derived from the grain refining due to the grain boundary pinning effect of Sc oxide. Microstructure observation before and after tensile deformation shows that the shape memory effect in Ti-Sc-Mo alloys is associated with stress induced $\beta \rightarrow \alpha''$ martensitic transformation. According to these features, Ti-Sc-Mo alloys are promising as a new biomedical material.

REFERENCES

[1] S. A. Shabalovskaya, International Materials Reviews Vol. 46 No.5 233-250 (2001).

[2] H. Hosoda, N. Hosoda and S. Miyazaki, Transactions of the Materials Research Society of Japan 26 [1] (2001) 243-246.

[3] H. Hosoda, Y. Ohmatsu and S. Miyazaki, Transactions of the Materials Research Society of Japan 26 [1] (2001) 243-246.

[4] E. Takahashi, T. Sakurai, S. Watanabe, N, Masahashi and S. Hanada, Materials Transactions, JIM, Vol. 43, No. 12 (2002) 2978-2983.

[5] D. Kuroda, M. Niinomi, M. Morinaga, Y. Kato and T. Yashiro, Materials Science and Engineering A243 244-249 (1998).

[6] C. Y. Lei, J. S. Lee Pak, H. R. P. Inoue and C. Marvin Wayman, Proc. of International Conference on Martensitic Transformation (1992) 533-537.

[7] T. Furuhara, T. Makino, Y. Idei, H. Ishigaki, A. Takada and T. Maki, Materials Transactions, JIM, Vol. 39, No. 1 (1998) 39-39.

[8] H. Sasano and T. Suzuki, Proc. Int. conf. of Titanium, 1984, Vol. 3, 1667-1674.

[9] T. Hamada, T. Sodeoka and M. Miyagi, Proc. Int. Conf. of Titanium, 1988, Vol 2, 877-889.

[10]T. Sugimoto, M, Ikeda, S. Komatsu, K. Sugimoto and K. Kamei, Proc. Int. Conf. of Titanium, 1988, 1069-1074.

(Received October 10, 2003; Accepted March 20, 2004)