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Thermomechanical Properties of Ti-Mo-Sn Alloys

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This paper describes effects of temperature and applied strain on thermomechanical properties of Ni-free Ti-Mo-Sn alloys. The materials used are Ti-6Mo-4Sn, Ti-5Mo-5Sn, Ti-5Mo-4.6Sn and Ti-4.4Mo-5.6Sn (mol%). Loading-unloading tensile tests were carried out under the applied strain of 3% at temperatures between 183K and 323K. Additionally, loading-unloading tensile tests were carried out under the applied strains ranging from 1% to 6% at 183K. Young's modulus decreases with increasing temperature. Ti-5Mo-4.6Sn shows the smallest young's modulus at temperature above approximately 215K. There is a decrease in the critical stress for inducing martensites with increasing temperature. The largest critical stress for inducing martensites is found in Ti-6Mo-4Sn. Also, the critical stress for inducing martensites increases with increasing Mo content, in contrast, decreases with increasing Sn content. There is a decrease in the superelastic recovery strain with increasing temperature. Ti-5Mo-5Sn showed the largest superelastic recovery strain of nearly 2% under the applied strain of 4% at 183K.

Key words: biomedical materials, Ti-Mo-Sn alloys, superelasticity, effect of temperature, effect of applied strain

1. INTRODUCTION

Shape memory alloys (SMAs) have unique properties known as shape memory effect and superelasticity within a certain temperature range [1-4]. In addition, SMAs have high biocompatibility and low Young's modulus compared with normal metals [5-8]. Since Ti-Ni alloys have superior shape memory and superelastic properties and superior corrosion resistance in all SMAs [9-11], they have been applied as biomedical materials [12-14]. However, it has been reported that pure Ni is a toxic element and causes Ni-hypersensitivity. Although clear Ni-hypersensitivity to human body in Ti-Ni alloys has not been reported yet, its risk has been pointed out because Ti-Ni alloys contain about 50mol% of Ni. Therefore, it is preferable to develop safe Ni-free Ti based shape memory alloys. Many β-type Ti-based alloys have been confirmed in Ti-Nb based alloys and Ti-Mo based alloys.

In this study, to investigate thermomechanical properties, such as critical stress for inducing martensite and recovery strain, loading-unloading tensile tests were carried out using Ti-Mo-Sn alloys.

2. EXPERIMENTAL PROCEDURES

The chemical compositions of Ti-Mo-Sn alloys are Ti-6Mo-4Sn, Ti-5Mo-5Sn, Ti-5Mo-4.6Sn and Ti-4.4Mo-5.6Sn (mol%). The Ti-Mo-Sn alloys were prepared by Ar arc melting method using high purity elements Ti, Mo, and Sn. Specimens used in this study are sheet specimen with the thickness of 0.25mm and wire specimen with the diameter of 0.35mm and 1.0mm. They were processed in the following manner; the ingots of the Ti-Mo-Sn alloys were hot forged and hot rolled at 1073K followed by cold rolled and annealed at 1073K. Furthermore, specimens were heated at 1073K for 5min in air, and then quenched into water. The processing rates of the sheet and wire specimens are 58% and 36%, respectively. Also, gauge lengths of the sheet and wire specimens are 70mm and 34.4mm, respectively.

In this study, loading-unloading tensile tests were carried out using the sheet and wire specimens. Figure 1 shows a schematic diagram of stress-strain curve in the loading-unloading tensile test.[15-16] Young's modulus(E), critical stress for inducing martensite(σ_t), applied strain(ε), total recovery strain(ε_t), residual strain(ε_{re}), elastic recovery strain(ε_e) and superelasticity recovery strain(ε_{se}) are defined as shown in Fig.1. E is defined as the inclination of the straight

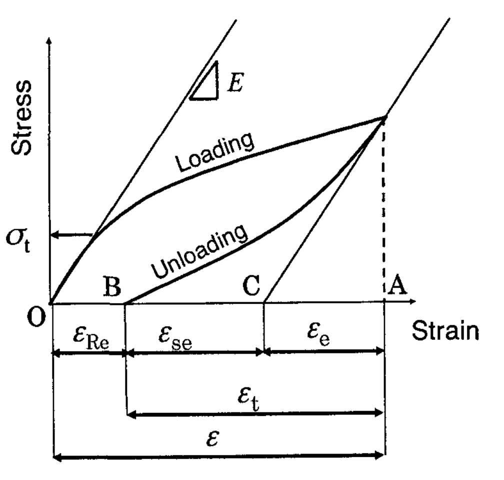

Fig.1 Schematic drawing of stress-strain curve.

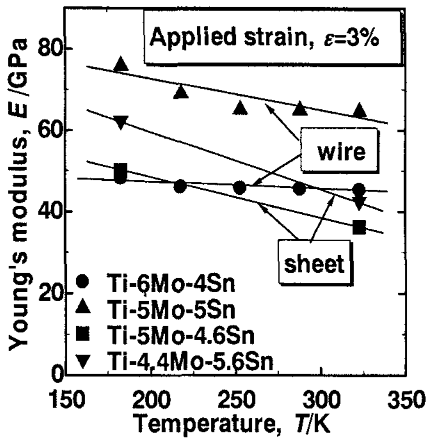

Fig.2 Variation of Young's modulus with temperature.

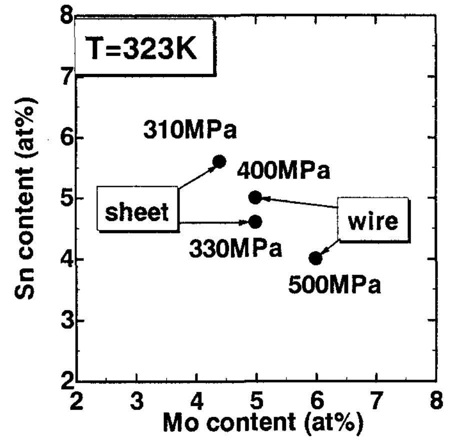

Fig.4 Relationship between critical stress for inducing martensites and contents of Mo and Sn.

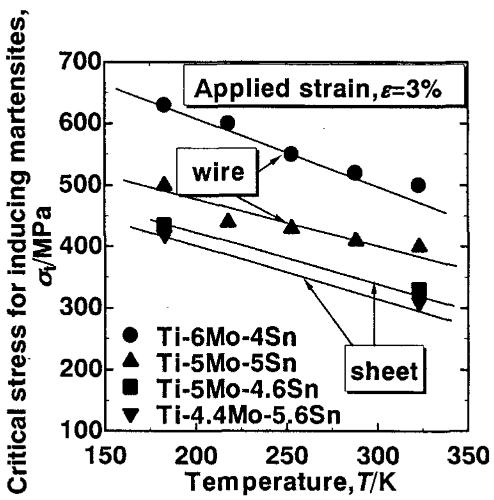

Fig.3 Variation of critical stress for inducing martensites with temperature.

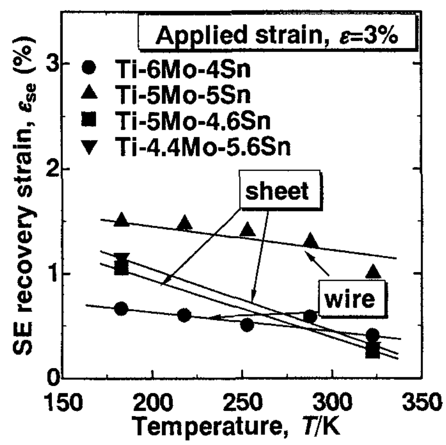

Fig.5 Variation of superelastic recovery strain with temperature.

line portion of the stress-strain curve. ε (O-A) is the maximum applied strain of the specimen under tensile loading. σ_t is defined as the stress at which the stress-strain curve deviates from the straight line portion of the stress-strain curve. ε_t (A-B) and ε_{re} (O-B) are the recovered strain and remained strain after unloading, respectively. ε_e (A-C) is defined as the resiliently recovered strain, and ε_{se} (B-C) is the recovered strain due to superelastic behavior.

3. RESULTS AND DISCUSSION

3.1 Effect of temperature on thermomechanical properties

To investigate the effect of temperature on thermomechanical properties, loading-unloading tensile tests were carried out under the applied strain of 3% at temperatures between 183K and 323K.

Figure 2 shows the variation of Young's modulus with temperature in the Ti-Mo-Sn alloys. Young's modulus of the Ti-Mo-Sn alloys decreases with increasing temperature. However, the decrease in Young's modulus of Ti-6Mo-4Sn is very small compared to other Ti-Mo-Sn alloys. Also, the smallest young's modulus is shown in Ti-5Mo-4.6Sn and the largest Ti-5Mo-5Sn at temperature above approximately 215K. In the comparison of the wire specimens, Young's modulus of Ti-6Mo-4Sn is smaller than that of Ti-5Mo-5Sn. On the other hand, in the comparison of the sheet specimens, Young's modulus of Ti-5Mo-4.6Sn is smaller than that of Ti-4.4Mo-5.6Sn. From these results, it is found that the Young's modulus decreases with increasing Mo content and decreasing Sn content.

Figure 3 shows the variation of the critical stress for inducing martensites with temperature. There is a decrease in the critical stress for inducing martensites with increasing temperature in all alloys since the dislocation density decreases with increasing temperature. Furthermore, the dislocation density of the wire specimens is larger than that of the sheet specimens, so that the critical stress for inducing martensites of the wire specimens is larger than those of the sheet specimens. Also, the largest critical stress for inducing martensites is found in Ti-6Mo-4Sn.

Figure 4 shows the relationship between the critical stress for inducing martensites and the contents of Mo and Sn at 323K. In the case of the wire specimens, the critical stress for inducing martensites of Ti-6Mo-4Sn is lager than that of Ti-5Mo-5Sn, and in the case of the sheet specimens, the critical stress for inducing martensites of Ti-5.0Mo-4.6Sn is slightly larger than

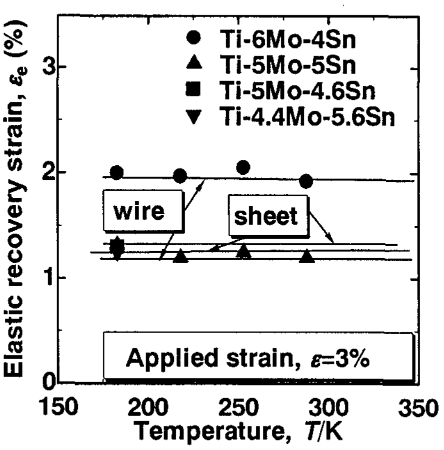

Fig.6 Variation of elastic recovery strain with temperature.

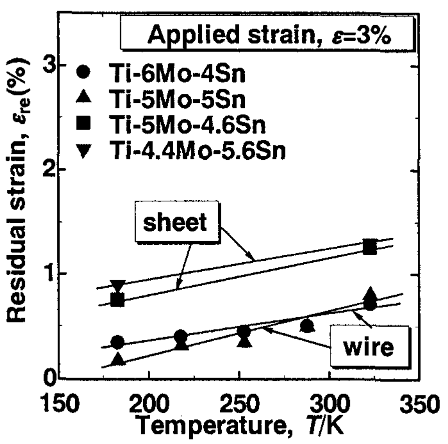

Fig.7 Variation of residual strain with temperature.

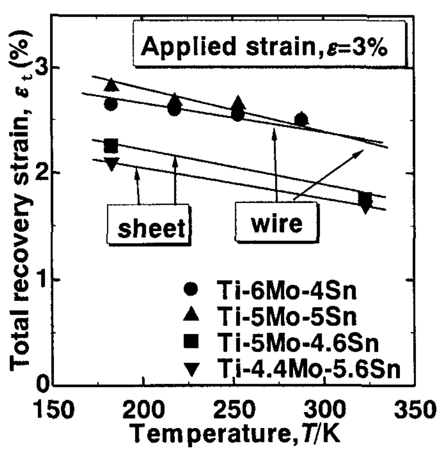

Fig.8 Variation of total recovery strain with temperature.

that of Ti-4.4Mo-5.6Sn. These indicate that the critical stress for inducing martensites tends to increase with increasing Mo content, in contrast, decrease with increasing Sn content.

The variation of the superelastic recovery strain with temperature is shown in Fig. 5. There was a decrease

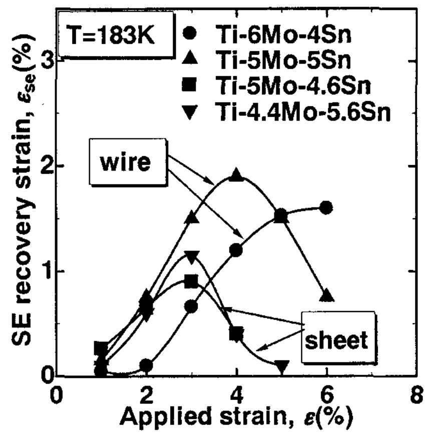

Fig.9 Variation of superelastic recovery strain with applied strain.

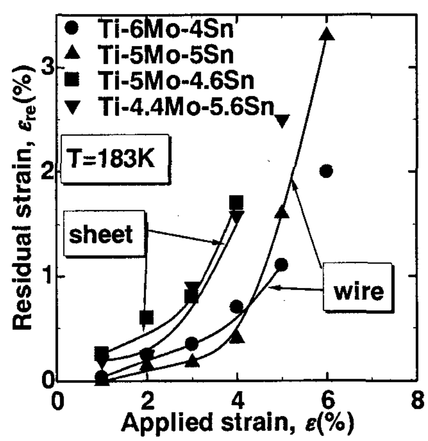

Fig.10 Variation of residual strain with applied strain.

in the superelastic recovery strain with increasing temperature in the Ti-Mo-Sn alloys. The degrees of the reduction in the wire specimens are gentler than those in the sheet specimens. The slip deformation get preference over the stress induced martensite transformation above a certain temperature, so that the strain remains as the permanent strain. Therefore, the superelastic recovery strain decreases with increasing temperature. Also, the superelastic recovery strain increases with decreasing Mo content and increasing Sn content but the increase in the superelastic recovery strain of the sheet specimens is small. The largest superelastic recovery strain is found in Ti-5Mo-5Sn.

Figure 6 shows the variation of the elastic recovery strain with temperature. The elastic recovery strain of the alloys is almost constant at temperatures between 183K and 323K. In case of decreasing Young's modulus with increasing temperature, the elastic recovery strain increases. However, the critical stress for inducing martensite also decreases with increasing temperature resulting in the constant elastic recovery strain. Therefore, the effect of temperature on the elastic recovery strains is not observed. Also, Ti-6Mo-4Sn shows the largest elastic recovery strain which was approximately 2%. On the other hand, the elastic recovery strains of the other alloys are between

1.2 % and 1.4%.

Figure 7 shows the variation of the residual strain with temperature. The residual strain of the alloys increases with increasing temperature because the slip deformation get preference over the stress induced martensite transformation with increasing temperature. The residual strain of the sheet specimens is larger than those of the wire specimens because the critical stress for inducing martensites of the sheet specimen is smaller than that of the wire specimen.

Figure 8 shows the variation of the total recovery strain with temperature. The total strain increases correspond to the superelastic recovery strain increases with increasing temperature since the total strain is comprised of the superelastic strain and the elastic strain.

3.2 Effect of applied strain on thermomechanical properties

To examine the effect of applied strain on thermomechanical properties, loading-unloading tensile tests were carried out under applied strains ranging from 1% to 6% at 183K.

Figure 9 shows the variation of the superelastic recovery strain with applied strain at 183K. Ti-5Mo-5Sn shows the largest superelastic recovery strain of nearly 2% under the applied strain of 4%. The superelastic recovery strain of Ti-6Mo-4Sn increases with increasing applied strain, and then it is saturated at the applied strain of about 6%. On the other hand, the peak superelastic recovery strains of Ti-5Mo-4.6Sn and Ti-4.4Mo-5.6Sn employed for the sheet specimen appeared at the applied strain of approximately 3%, and they were smaller than those of the wire specimen.

The variation of the residual strain with applied strain at 183K is shown in Fig.10. The residual strain nonlinearly increases with increasing applied strain. The residual strain gradually increases with increasing applied strain at first, and then it widely increases with more than the applied strain which showed the peak superelastic strain in Fig.9.

The superelastic recovery strain increases with increasing applied strain up to a certain degree. However, the residual strain widely increases with increasing damage, so that the superelastic recovery strain decreases.

4. CONCLUSION

To investigate the effect of temperature on thermomechanical properties, loading-unloading tensile tests have been carried out under the applied strain of 3% at temperatures between 183K and 323K. Additionally, to examine the effect of applied strain on thermomechanical properties, loading-unloading tensile tests were carried out under applied strains ranging from 1% to 6% at 183K.

(1) Young's modulus has decreased with increasing temperature. Ti-5Mo-4.6Sn has showed the smallest young's modulus at temperature above approximately 215K.

(2) There has been a decrease in the critical stress for inducing martensites with increasing temperature. The largest critical stress for inducing martensites has been found in Ti-6Mo-4Sn. Also, the critical stress for inducing martensites has increased with increasing Mo content, in contrast, has decreased with increasing Sn content.

(3) There has been a decrease in the superelastic recovery strain with increasing temperature. Ti-5Mo-5Sn has showed the largest superelastic recovery strain of nearly 2% under the applied strain of 4% at 183K.

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