Development of novel titanium alloys with changeable Young's modulus for spinal fixation rods applications

***[Introduction]** Implanting metallic rods plays an important role in the treatment of scoliosis et al. [1]. However, the demands of surgeons and patients in terms of Young's modulus are opposite. In this study, deformation-induced phase transformation was taken advantage of to meet the demands of both surgeons and patients.*

[Alloy design] The novel alloys in this study were designed by Mo equivalents (Mo_{eq}) [2], as shown in eq. (1), in the metastable range, $5 \leqq Mo_{eq} \leqq 7$ (mass%) because the deformation-induced phase transformation will occur in the range of Mo_{eq} in the previous report [3].

$$\mathrm{Moeq} = [\mathrm{Mo}] + [\mathrm{Ta}]/5 + [\mathrm{Nb}]/3.5 + [\mathrm{W}]/2.5 + [\mathrm{V}]/1.5 + 1.25[\mathrm{Cr}] + \dots \ (\text{mass\%}) \qquad (1)$$

Based on above concept, Ti-30Zr-4Cr, Ti-30Zr-5Cr, Ti-30Zr-1Cr-5Mo, Ti-30Zr-2Cr-4Mo, and Ti-30Zr-3Cr-3Mo alloys, which Mo_{eq} are 5.00, 6.25, 6.25, 6.50, and 6.75, respectively, (hereafter, these alloys are denoted by 4Cr, 5Cr, 1Cr5Mo, 2Cr4Mo, and 3Cr3Mo, respectively) were designed.

[Materials and methods] The designed alloys (Ti-30Zr-(Cr, Mo)) were prepared by arc melting with a non-consumable tungsten electrode under a high purity argon atmosphere. The ingots obtained were homogenized at 1373 K for 21.6 ks and then hot rolled into plates with a reduction ratio of around 70% at 1273 K (both processes were heated in an argon atmosphere), after which ice-water quenching and air cooling were carried out. Then the hot rolled plates were solution treated in vacuum at 1123 K for 3.6 ks and quenched in ice-water. Some of the solutionized plates were cold rolled with a reduction ratio of around 10% at room temperature. As the final treatment, the solution treatment and cold rolling were labeled as ST and CR, respectively. The phase constitution was identified by X-ray diffraction (XRD) analysis. The microstructures were observed by optical microscopy (OM) using a differential interference contrast microscope, electron backscattered diffraction (EBSD) analysis and transmission electron microscopy (TEM). The mechanical properties were evaluated by Young's modulus measurements, tensile tests, and tensile loading-unloading tests.

[Results and discussion] After solution treatment, each of the Ti-30Zr-(Cr, Mo) alloys consists of equiaxed β phase and tiny dispersive ω phase, which were observed by TEM. The intensity of the athermal ω phase decreases with increase in the Mo equivalence.

After cold rolling with reductuion ratio of 10%, deformation-induced phase transformations occurs in all the alloys; the deformation-induced products in Ti-30Zr-4Cr, Ti-30Zr-1Cr-5Mo, Ti-30Zr-2Cr-4Mo, Ti-30Zr-3Cr-3Mo are deformation-induced α′ phase and deformation-induced {332}<113> mechanical twin. The ratio of amount of deformation-induced α′ phase to deformation-induced {332}<113> mechanical twin decreases with increase in the Mo equivalence. On the other hand, in Ti-30Zr-5Cr, only the deformation-induced {332}<113> mechanical twin and planar slip can be observed. The results of TEM observation indicates that deformation-induced ω phase transformation mainly occurs accompanying with the deformation-induced {332}<113> mechanical twinning.

Figure 1 shows the Young's moduli variation of each alloys subjected to solution treatment and cold rolling. All the novel designed alloys exhibits low Young's moduli of <70 GPa; this value is much lower than those of SUS 316L stainless steel (SUS 316L), commercially pure titanium (CP Ti), and Ti-6Al-4V ELI alloy (Ti64 ELI) [3], which are currently widely used for spinal fixation applications. After cold rolling, the Young's moduli of 4Cr and 1Cr5Mo decreased slightly compared with those under ST conditions. However, the Young's moduli of 5Cr, 2Cr4Mo, and 3Cr3Mo increased by cold rolling, with those of 5Cr and 3Cr3Mo increasing in the range of $P < 0.05$. The Young's modulus of 3Cr3Mo after cold rolling increases to around 80 GPa with an increase ratio of 15%. In Ti-30Zr-Cr-Mo alloys, the difference between the Young's moduli under ST and CR conditions varies with the phase constitution. As mentioned above, under CR conditions, the amount of deformation-induced α' phase decreases with an increasing in the Mo equivalent; the deformation-induced α' phase disappears in 5Cr. It is reported that the α' phase exhibited a lower Young's modulus than that of β phase [4, 5]. Therefore, the decreasing of the Young's moduli of 4Cr and 1Cr5Mo after cold rolling could be attributed to the deformation-induced α' phase. In the cold rolled 5Cr, 2Cr4Mo, and 3Cr3Mo alloys, since the {332}<113> mechanical twin can be found, the increasing of the Young's moduli are considered to be related to the {332}<113> mechanical twin. It is clear that the deformation-induced ω phase transformation frequently occurs accompanying with the deformation-induced {332}<113> mechanical twinning. It is known that the Young's modulus of ω phase is higher than that of other phases in titanium alloys. Therefore, the increasing of Young's moduli in 5Cr, 2Cr4Mo, and 3Cr3Mo after cold rolling are attributed to the deformation-induced ω phase.

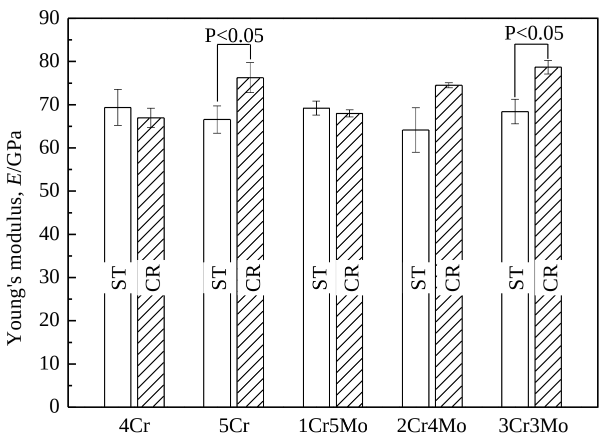

Fig. 1 Young's moduli of Ti-30Zr-(Cr, Mo) alloys subjected to solution treatment (ST) and cold rolling (CR).

[Summary] In summary, after solution treatment, Young's moduli of the alloys are lower than those of the conventional alloys such as SUS 316L, CP Ti, and Ti64 ELI, which offers the possiblity to prevent the stress-shielding effect after surgery. After deformation, Young's moduli increases with deformation-induced ω phase, which provides the possibility to suppress the springback. Fig. 2 shows the springback of 3Cr3Mo with deformation-induced ω phase and TNTZ, without any deformation-induced phase transformation.The loading-unloading tests indicate that the springback of Ti-30Zr-3Cr-3Mo with deformation-induced ω phase transformation is smaller than that of TNTZ without deformation-induced phase transformation. In addition, the tensile properties of Ti-30Zr-3Cr-3Mo show a good balance, providing potential for practical applications.

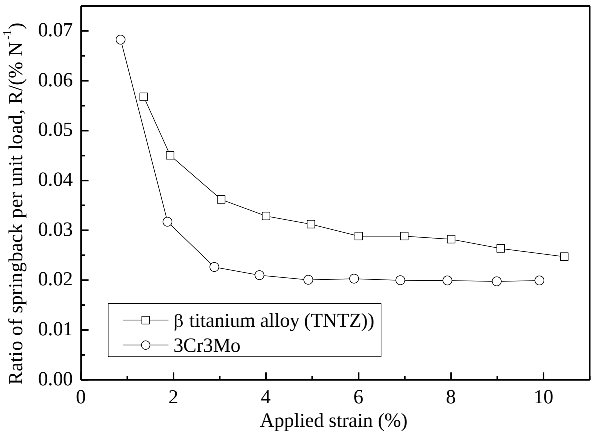

Fig. 2 Ratio of springback per unit load as a function of applied strain for 3Cr3MO and TNTZ, and strains for calculation of springback ratio (inset).

References

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Key Words

Titanium alloys, deformation-induced, spring back

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