Zirconium Alloy with Excellent Mechanical Property to Decrease MRI Artifact

Takao Hanawa[1,2], Maki Ashida[1], Yusuke Tsutsumi[3], Peng Chen[1], Naoyuki Nomura[4]

[1] Institute of Biomaterials and Bioengineering, Tokyo Medical and Dental University, Japan
[2] Center for Advanced Medical Engineering Research and Development, Kobe University, Japan
[3] Strructual Matrials Group, National Institute for Materials Science, Japan
[4] Graduate School of Engineering, Tohoku University, Japan

Abstract

INTRODUCTION
Metals implanted into the human body have sometimes higher magnetic susceptibility than the surrounding tissues. Therefore magnetic resonance imaging (MRI) diagnosing is disturbed by artifacts appearing on the MR images. In our previous study, Zr-1Mo alloy with low magnetic susceptibility is developed [1-4] and generates much smaller artifact than Ti-6Al-4V ELI alloy. In this study, based on d-electron alloy design method and empirical data of binary Zr alloys, Zr-14Nb-5Ta-1Mo alloy was designed and mechanical properties, magnetic susceptibility, corrosion resistance, and cytocompatibility were evaluated.
METHODS
Based on d-electron alloy design method and empirical data of binary Zr-Nb, Zr-Mo and Zr-Ta alloys, composition of alloys were determined. The new designed alloy was fabricated by induction skull melting, followed by forging at 1050˚ C. A rod with 5 mmf was obtained through electrical discharge machining. Then, cold swaging was performed to 56% and 97%. In addition, heat treatment was performed to all specimens: heated at 400˚ C for 45 min and quenched in iced water. The crystal phase structure was characterized using XRD and TEM. Mechanical property was evaluated by tensile test and Vickers hardness test. Moreover, corrosion resistance and cytocompatibility were evaluated.
RESULTS AND DISCUSSION
The composition of alloys were determined as Zr-14Nb-5Ta-1Mo (mass%). There is no macro-segregation in the ingot of the alloy. Hot forging and cold swaging are performed without any fracture of the specimen. The alloy was constituted of □ phase with a small amount of □ phase and/or □ phase. Stress-strain curves of Zr-14Nb-5Ta-1Mo alloy after working are shown in Figure 2. As summarized in Table 1 [5], in the case of 97% cold swaging, tensile strength was 1054 MPa, 0.2% proof strength was 1011 MPa, elongation to fracture was 16%, Vickers hardness was 258, and Youngs' modulus was 67 GPa. The mass magnetic susceptibility was 18.1 x 10-9 m3kg-1. After heat treatment, Tensile strength 0.2% proof strength, and Vickers hardness increased remaining Youngs' modulus and magnetic susceptibility. The corrosion resistance of the alloy was increased with swaging. In addition, this alloy did not show any cytotoxicity.
CONCLUSION
Zr-14Nb-5Ta-1Mo alloy has excellent balance of mechanical property with low magnetic susceptibility, high corrosion resistance, and no cytotoxicity. This alloy achieves large strength and elongation with small Youngs' modulus that is not acquired in conventional Ti alloys. In addition, magnetic susceptibility was half of titanium alloys. Therefore, Zr-14Nb-5Ta-1Mo alloy is a promising metallic materials to decrease MRI artifact.
REFERENCES
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ACKNOWLEDGMENTS
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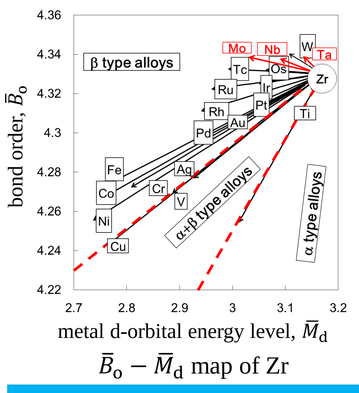
Alloy Design



$\bar{B}_o - \bar{M}_d$ map of Zr

In this study, it is required alloying elements are…

- **In β phase**
- **Low cytotoxicity**
- **Low magnetic susceptibility**

We employed…

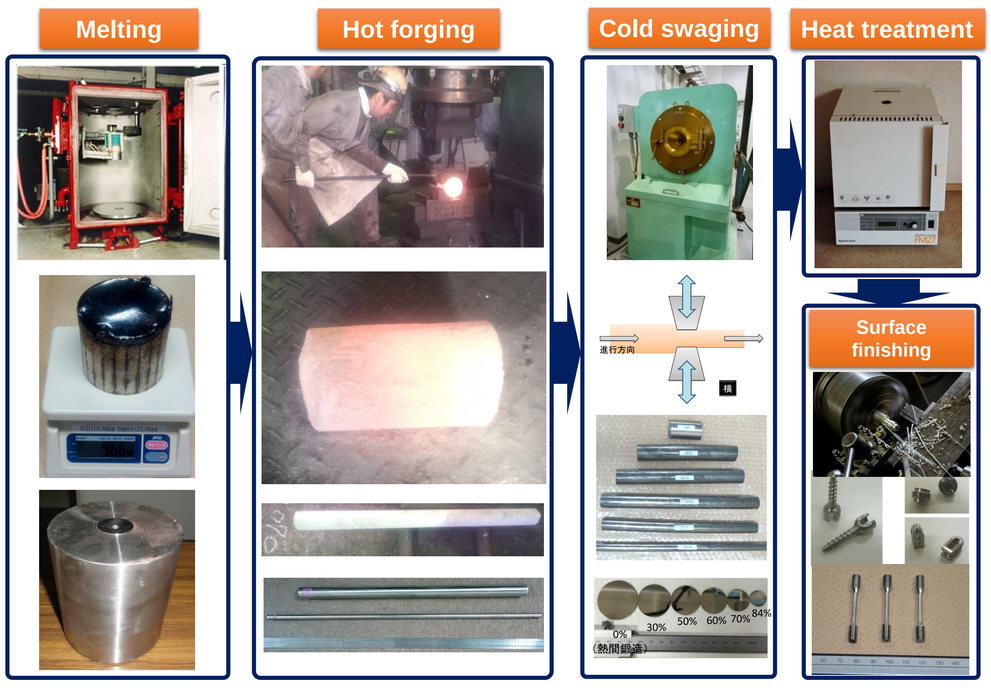
Nb, Mo, Ta

for additional elements

In reference to previous study about binary Zr…

Zr-14Nb-5Ta-1Mo

Manufacturing Process



Ingot melting
- Zr-14Nb-5Ta-1Mo
- ϕ130 mm; 6 kg
- Cold Crucible Induction Melting Furnace
- Ar atmosphre

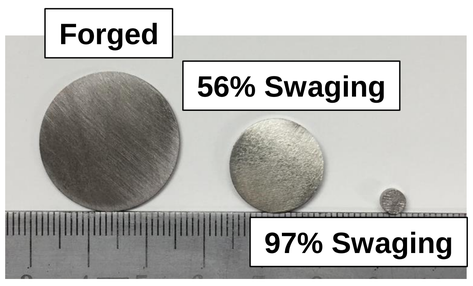
XRF
- Evaluation of composition unity

Turning process
- Removal of 1-2 mm surface

Hot forging
- 1050℃; ϕ32 mm

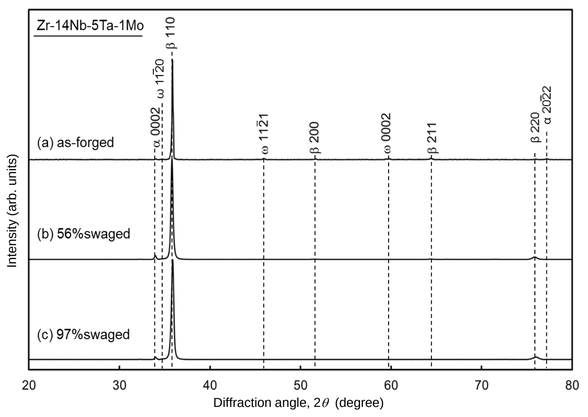
Turning process
- Removal 4 mm surface
- ϕ24 mm

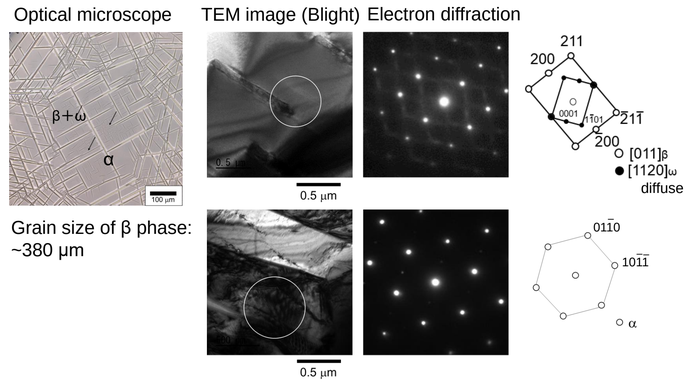
Cold swaging
- Room Temperature
- ϕ16.2 mm, 4 mm
- R_A: 56% R_A: 97%



97% working was feasible
Good workability

XRD and TEM of forged alloy

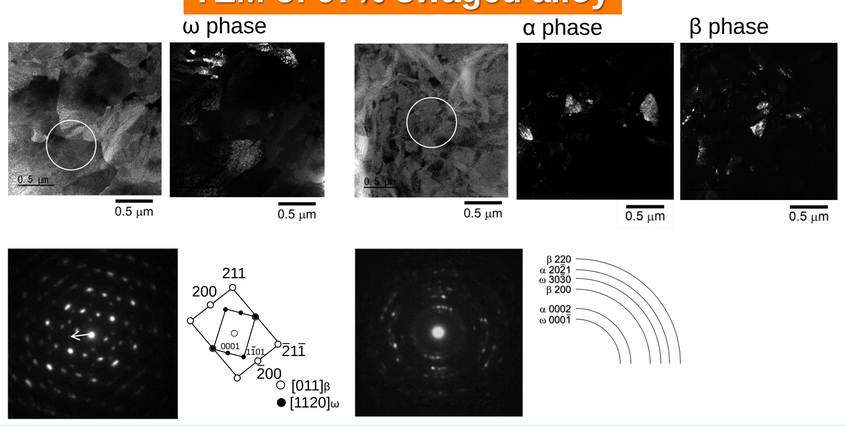




Grain size of β phase: ~380 μm

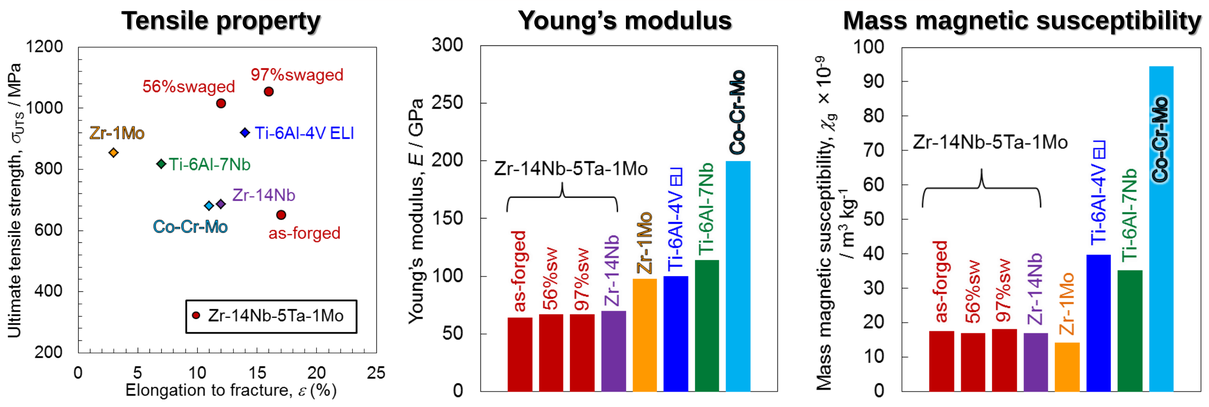
Structure: Needle-like α and ω phase existed in Matrix β phase

TEM of 97% swaged alloy



Both needle-like α and β phases were refined by cold swaging.

Mechanical properties and susceptibility



Composition	Young's modulus, E / GPa	Ultimate tensile strength, σ_{UTS} / MPa	0.2% proof strength, $\sigma_{0.2\%}$ / MPa	Elongation to fracture, ε / %	Vickers hardness, HV	Mass magnetic susceptibility, χ_g / $10^{-9}m^3 \cdot kg^{-1}$
As-forged	**64±1**	**651±13**	**632±13**	**17±7**	**213±8**	**17.5±0.4**
SW 56%	**67±1**	**1016±26**	**991±26**	**12±1**	**239±8**	**17.0±0.1**
SW 97%	**67±1**	**1054±30**	**1011±27**	**16±1**	**259±13**	**18.1±1.0**
Heat treated	**68±2**	**1033±23**	**986±17**	**9±1**	**261±8**	**16.8±0.4**
As-cast	53±1	796±64	754±57	15±4	208±1	17.3±0.2
Zr-14Nb (as cast)	70	784	686	12	275	17.0
Zr-1Mo (as cast)	98	970	855	3	---	14.2
Ti-6Al-4V ELI	100	980	920	14	320	39.8
Ti-6Al-7Nb	114	933	817	7	325	35.3
Co-Cr-Mo	200	980	680	11	370	94.5

Conclusions

- Cold swaging to 97% was feasible: Excellent workability.
- After 97% swaging, the ultimate tensile strength (1054 MPa) and elongation (16%) were better than those of Ti-6Al-4V ELI alloy.
- Low magnetic susceptibility and Young's modulus were remained after swaging.

The Zr-14Nb-5Ta-1Mo alloy could be used for MRI compatible devices.