Solid solution strengthening mechanisms of PM α-Ti materials with zirconium and oxygen atoms

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Introduction

Conventional titanium (Ti) alloys show high strength by addition of rare metals as alloying elements, causing less their biocompatibility required in application to medical devices. One of the representative high-strength Ti alloys used as biomaterials, for example, is Ti-6Al-4V (Ti-64). A solution to a toxicity problem by vanadium element is strongly required in Ti-64 alloy. In this study, focusing on complete solid-solution of zirconium (Zr) into α and β-Ti, which is one of the biocompatible elements, high-strength α-Ti material with Zr & oxygen solute atoms (Ti (Zr, O)) is fabricated by powder metallurgy (PM) process via solid-state reaction between pure Ti powder and ZrO_2 particles in sintering. Microstructural and mechanical properties of PM Ti (Zr, O) materials are investigated, and then their strengthening mechanism is clarified in detail through the microstructures analysis.

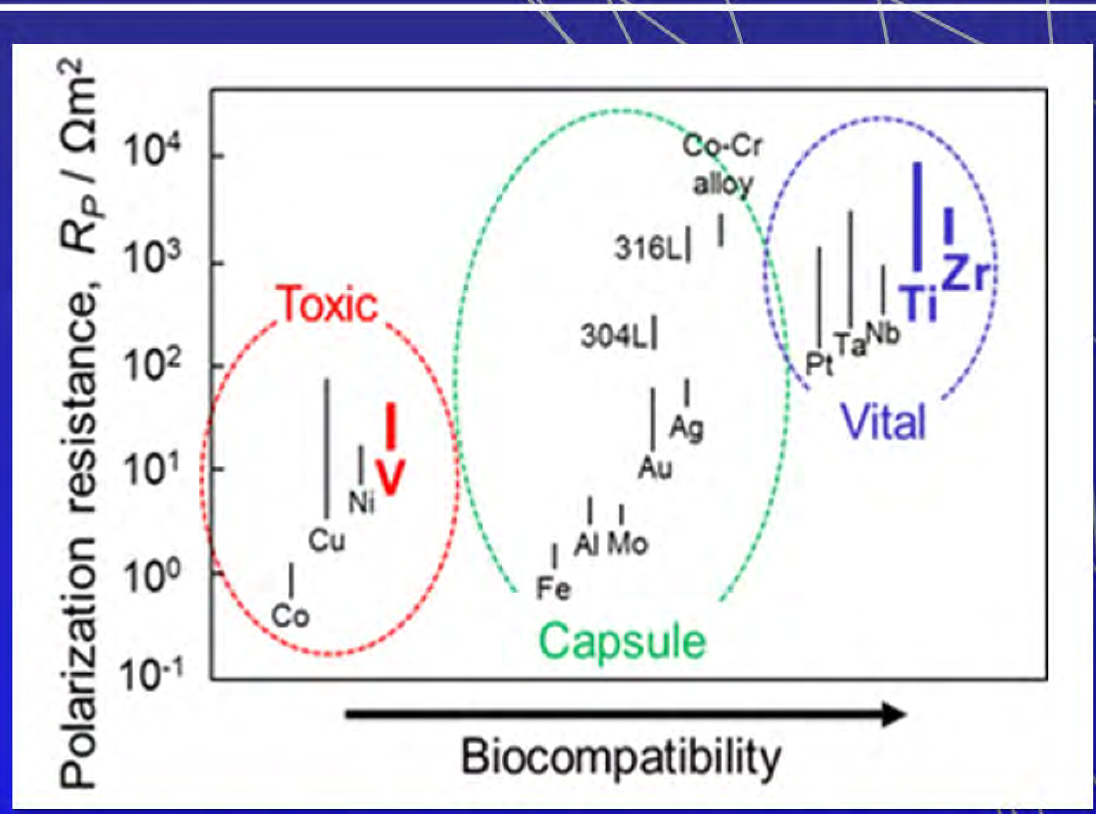
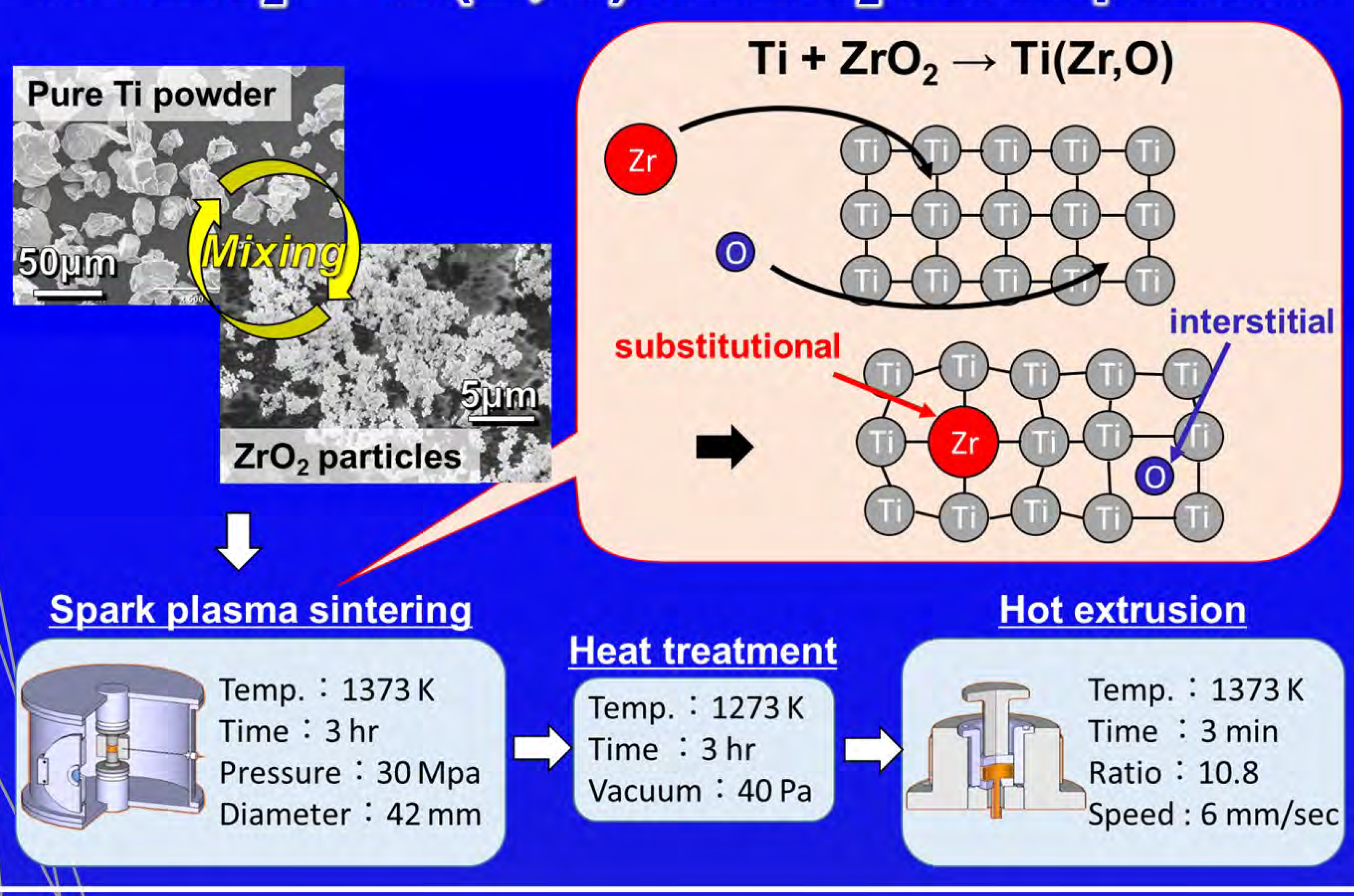
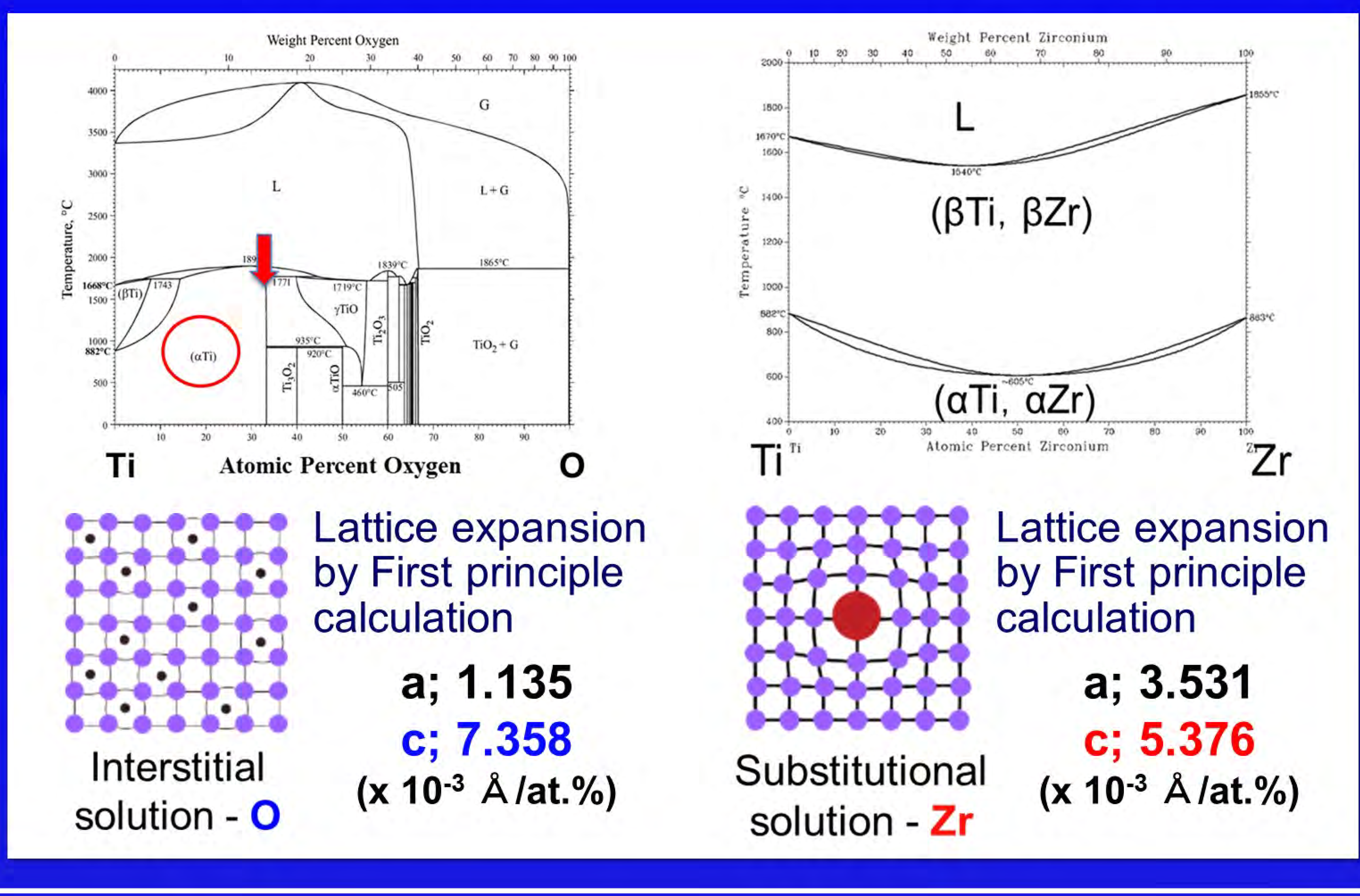


Fig. Relationship between polarization resistance and biocompatibility of pure metals, conventional Co-Cr alloy and stainless steel from a viewpoint of application of metals & their alloys to biomaterials & medical devices.

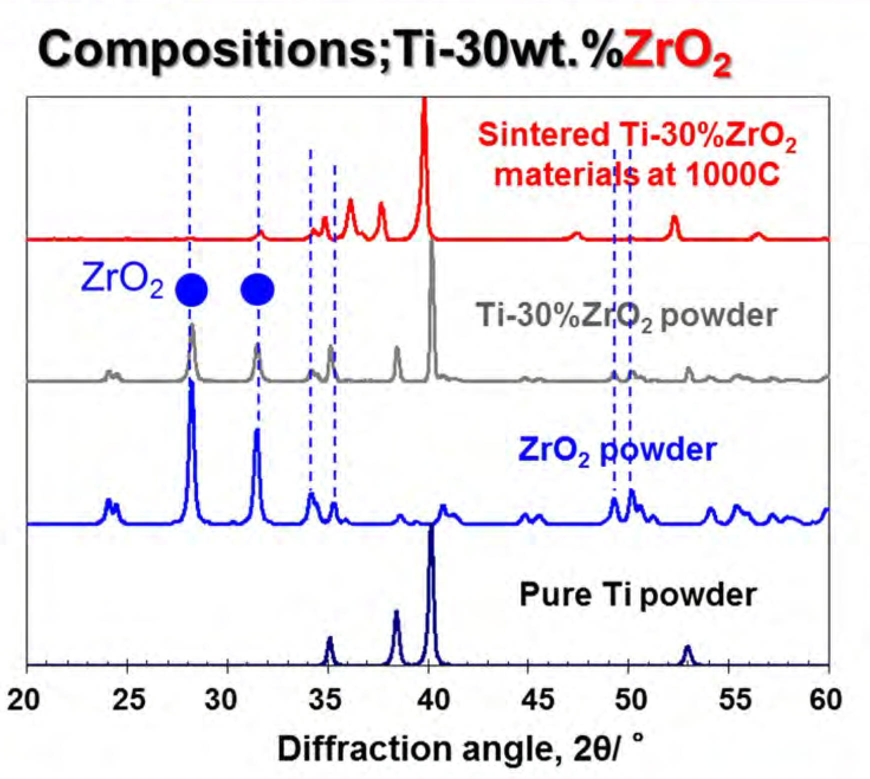
Experimental procedure

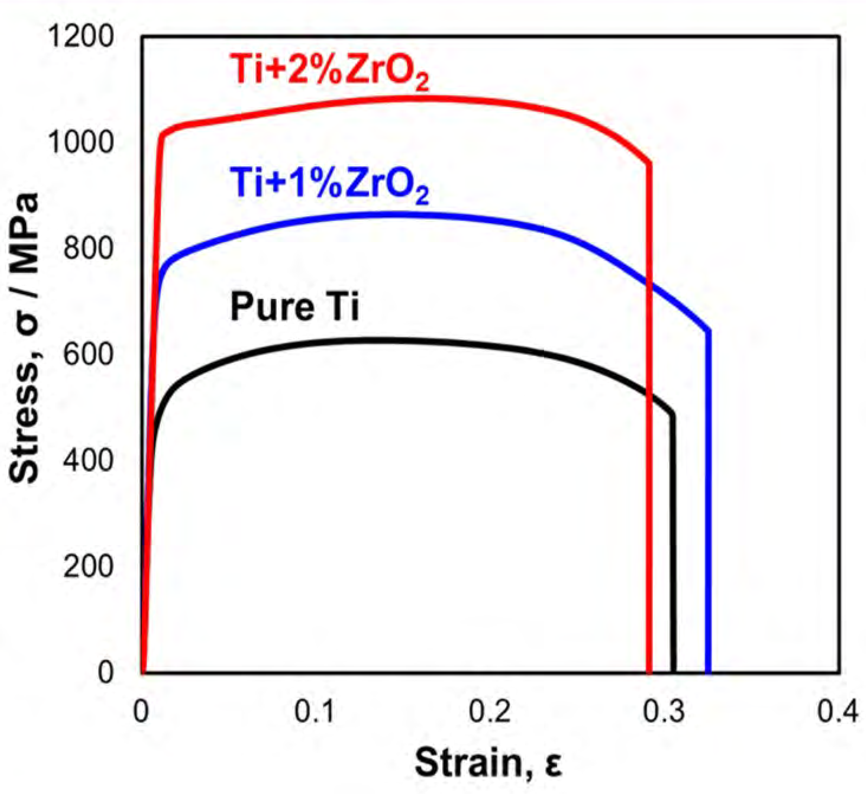
Ti + ZrO_2 ⇒ Ti (Zr, O) via ZrO_2 decomposition

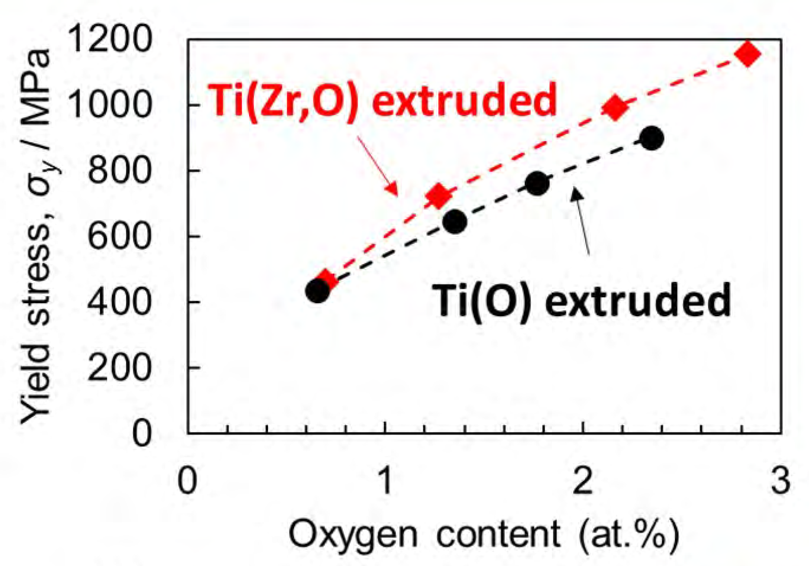


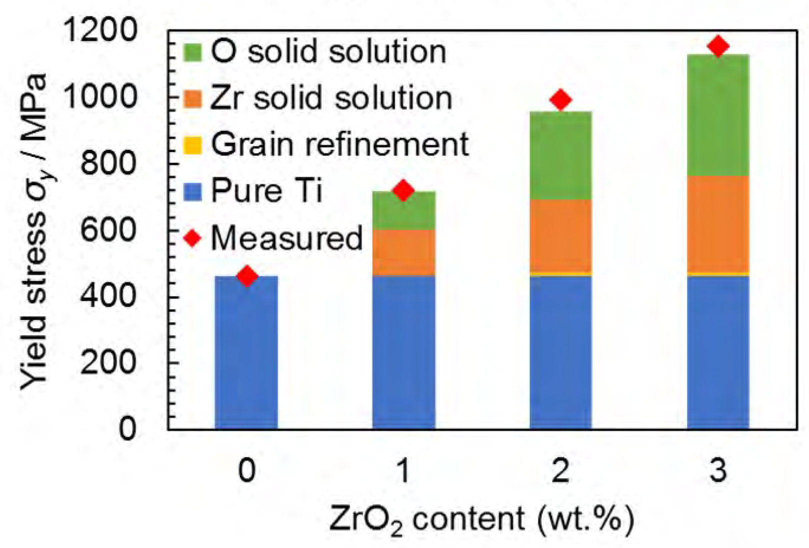


Results − Microstructural and mechanical properties



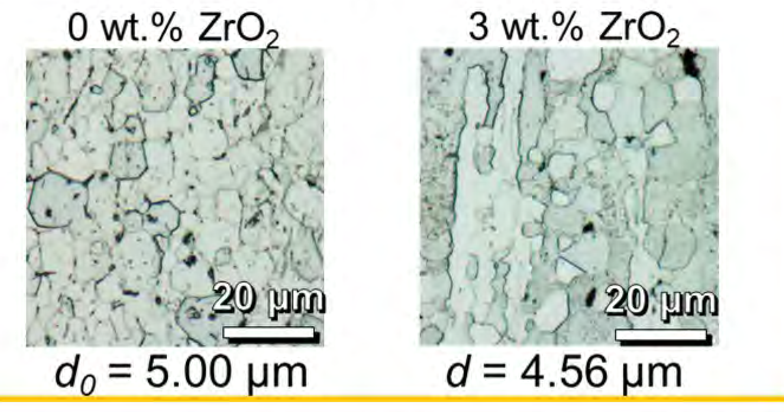


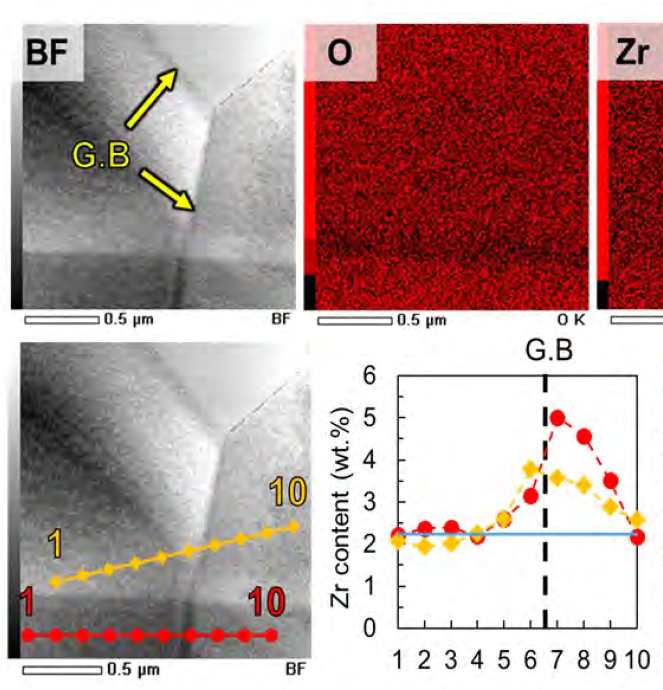




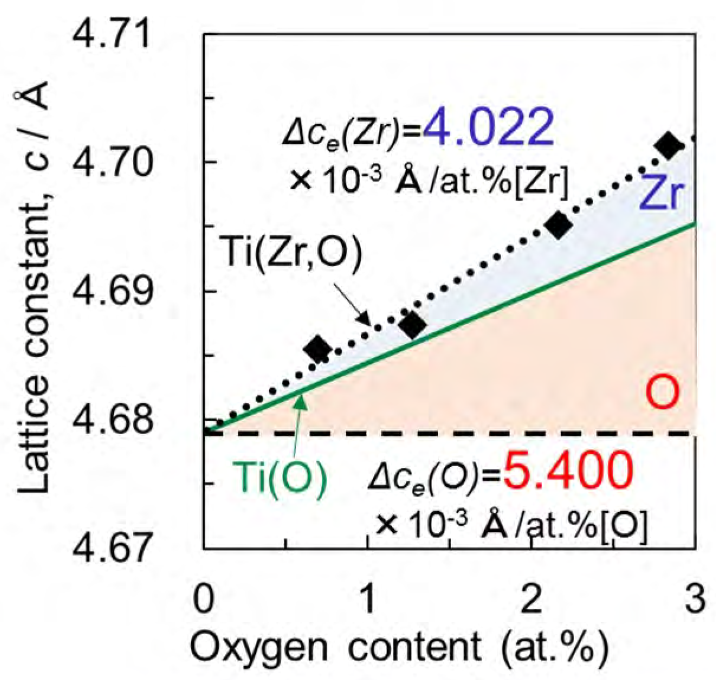
> **Strengthening by solid solute Zr, O**
>
> *Labusch-model*
>
> $$\Delta\sigma_y = \frac{\tau_0}{S_F} = \frac{1}{S_F}\left(\frac{F_m{}^4 c^2 w}{4Gb^9}\right)^{\frac{1}{3}}$$
>
> Solute atom / Dislocation
>
> τ_0: Shear stress S_F: Schmidt factor (0.41~0.45)
> F_m: Maximum of interaction between solute atom and dislocation
> c: Concentration of solute atoms
> w: Range of interaction between solute atom and dislocation(≒5b)
> G: Modulus of rigidity b: Burgers vector

> **Strengthening by grain refinement**
>
> *Hall-Petch equation* $\Delta\sigma_y = k(d^{1/2} - d_0{}^{1/2})$
>
> k: H-P coefficient (k = 18 MPa/mm$^{-1/2}$)





Agglomeration of Zr atoms at grain boundaries of Ti materials via solid-state reaction of pure Ti with ZrO_2 particles



- **Additive ZrO_2 particles were thermally decomposed by reaction with pure Ti powder more than 973 K, and dissolved Zr and O atoms resulted in the lattice expansion of α-Ti (hcp) crystal during sintering process (strengthening effect).**
- **Ti powder with 3 wt.% ZrO_2 particles showed 0.2% yield stress (YS) of 1153 MPa, which was greatly higher compared to pure Ti material with 463 MPa YS. The main strengthening factor of Ti (Zr, O) alloy was solid solution of Zr and O atoms in α-Ti.**