# Additively manufactured Ti-Zr alloys with gyroid lattice structures

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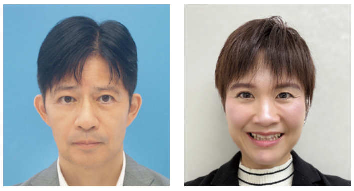

## Abstract

The objective was to develop a new high-strength titanium alloy for use in biomedical applications. The alloy was created using non-toxic components and three-dimensional complex structures were produced through metal additive manufacturing (AM). The mechanical properties of the alloy were then evaluated. Furthermore, a Ti-Zr alloy with enhanced strength and ductility was developed by incorporating zirconium (Zr), which exhibits comparable biocompatibility to titanium. This approach enabled the attainment of reduced rigidity through the implementation of internal space control via structural optimization. The research established guidelines for the design of a novel titanium alloy and manufacturing process for use in implantable medical devices, such as artificial bones, and demonstrated its versatility across a range of applications.

## Background & Results

Titanium exhibits high specific strength, excellent corrosion resistance, and biocompatibility. The Ti-6%Al-4%V (Ti64) alloy is a representative alloy that is widely used in a variety of applications, including those in the aerospace industry. Nevertheless, vanadium (V), an alloying element, is toxic, thereby necessitating the development of titanium alloys that can supplant Ti64 in biomedical applications, including implantable devices. Furthermore, the notable disparity in rigidity between titanium artificial bones and cortical bone can result in stress shielding, whereby specific bones are subjected to minimal or no load. Consequently, the lack of loading can result in atrophy and a reduction in bone strength. Potential solutions to this issue include the utilization of low-rigidity beta-type titanium alloys and the development of porous structures with the objective of reducing rigidity. In this study, we developed a high-strength Ti-Zr alloy with zirconium (Zr) as the alloying element, which demonstrated equal or superior cellular compatibility to titanium. An additive manufacturing (AM) approach was employed for the purpose of structural optimization, resulting in the creation of a gyroid structure composed of triple periodic minimal surfaces that extend infinitely. This was achieved by irradiating a mixture of pure Ti powder and zirconium hydride ($ZrH_2$) particles with a laser, thereby promoting in-situ alloying during the rapid melting and solidification process of the powder. The objective of this approach was to achieve solid solution strengthening of the $\alpha$-Ti phase and grain refinement (grain boundary strengthening) through the incorporation of Zr atoms. To illustrate, a comparison of the compressive properties of low-rigidity gyroid structures with compositions of Ti-7%$ZrH_2$ and Ti64 (with a porosity of approximately 67%) revealed that their rigidity and maximum compressive strength were nearly equivalent. With regard to the deformation behavior, the Ti64 alloy displayed a precipitous decline in stress as a consequence of local buckling and the failure of the cells that constituted the gyroid structure. In contrast, the Ti-Zr alloy exhibited uniform plastic deformation throughout the sample.

## Significance of the research and Future perspective

In the pursuit of a well-being society, it is of the utmost importance to provide a healthy, happy, and safe living environment for the elderly over the long term. To achieve this, the miniaturization and enhancement of the functionality of implantable components and systems, such as artificial bones, dental implants, and artificial heart devices, represent effective measures. The titanium alloy developed in this study has the potential to be a highly suitable material for this purpose. Conversely, when titanium components have reached the end of their functional lifespan, they are typically designed for one-way downgrade recycling, such as for use in steel production or as scrap disposal. Given that titanium is predominantly employed in specific resource applications, such as aircraft components, there is a compelling necessity to actively encourage research aimed at establishing advanced resource circulation (circular economy) processes that facilitate a positive cycle between the economy and the environment.

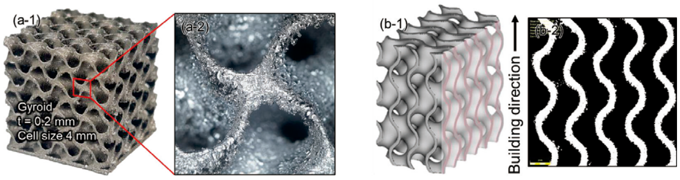


Fig.1 (a) Ti-7%$ZrH_2$ specimen with gyroid lattice structure and (b) optical microstructure of cross-section plane.

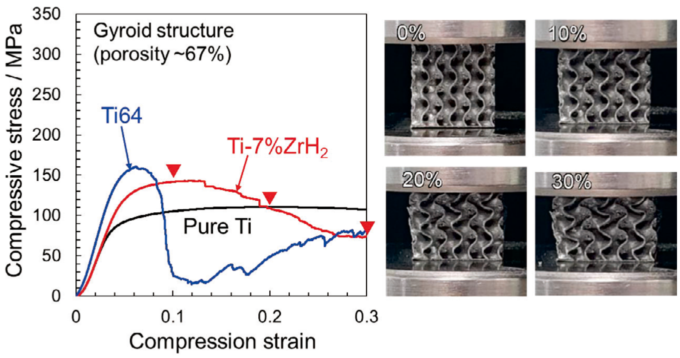


Fig.2 Compressive stress-strain curves of gyroid lattice structured specimen using Ti-7%$ZrH_2$ alloy, Ti64 alloy and pure Ti. In-situ observation on compression deformation behavior of Ti-7%$ZrH_2$ alloy (compression strain; 0~30%).

Patent

Treatise
Issariyapat, Ammarueda; Huang, Jeff; Kondoh, Katsuyoshi et al. Microstructure refinement and strengthening mechanisms of additively manufactured Ti-Zr alloys prepared from pre-mixed feedstock. Additive Manufacturing. 2023, 73, 103649. doi: 10.1016/j.addma.2023.103649
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Keyword titanium, zirconium, additive manufacturing, gyroid lattice structure