The 2019 World Congress on
Advances in Structural Engineering and Mechanics (ASEM19)
Jeju Island, Korea, September 17 - 21, 2019

Effect of oxygen on fatigue strength of spinal implant made of β titanium alloys

*Yoon-Seok Lee[1)] and Mitsuhiro Okayasu[2)]

[1), 2)] *Graduate School of Natural Science & Technology, Okayama University, Okayama 700-8530, Japan*
[1)] *y_lee@okayama-u.ac.jp*
[2)] *mitsuhiro.okayasu@utoronto.ca*

ABSTRACT

Titanium (Ti) alloys have been used as biomedical materials because of their good biocompatibility and high corrosion resistance. Ti alloys are used for biomedical applications, including in implant devices with metal-to-metal contacting parts. Spinal fixation devices consist of a rod, screw, and plug. In these devices, the activity of the patient could cause fretting of the metal-to-metal contacts between the rod and plug, which may result in failures. In this study, compressive fatigue tests were conducted with rods made of Ti–29Nb–13Ta–4.6Zr alloy with different oxygen contents. As a result of the compressive fatigue test, solid-solution strengthening by oxygen improves the fretting fatigue resistance of the Ti–29Nb–13Ta–4.6Zr rod.

1. INTRODUCTION

Ti alloys are often used for biomedical applications, including in implant devices with metal-to-metal contacting parts. Spinal fixation devices consist of three components; a rod, screw, and plug. The rod is fixed to the screw by mechanical fastening using the plugs. In these devices, the activity of the patient can cause fretting of the metal-to-metal contacts between the rod and plug. Failures have consequently occurred because of fretting in this system.

To evaluate the fatigue life of Ti spinal implants, two types of β-type Ti–29Nb–13Ta–4.6Zr (TNTZ) alloys were tested as rods, in this study. The first was a conventional TNTZ and the second was a TNTZ with high oxygen (O) content of 0.89 mass% for biomedical applications.

TNTZ exhibits good biocompatibility because of its nontoxicity, and a lower Young's modulus (approximately 60 GPa) than that of Ti64. However, the fatigue strength of TNTZ is not sufficient to satisfy the requirements of a long service life for

[1)] Assistant Professor
[2)] Professor

biomedical implants, even though this alloy exhibits good biocompatibility and a low Young's modulus. It is therefore necessary for TNTZ to further increase the resistance to fretting fatigue and concomitantly reduce the Young's modulus such that it approaches that of human bone.

The Young's modulus is related to the crystal structure, which is not significantly changed upon increasing the interstitial element content. From this viewpoint, interstitial elements are promising because their addition to TNTZ is expected to improve the plastic shear resistance, which could suppress the fretting fatigue failure via solid-solution strengthening. For the effect of solid-solution strengthening, low-cost O is used as an interstitial element in this study. Therefore, the mechanical performance of the spinal construct, consisting of the TNTZ rods with different O contents in air, was investigated in this study.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

The screws and plugs were constructed and assembled as per the manufacturer's recommendations. Ti64 was used as a plug and screw in this study. The materials used as a spinal rod in the present study were hot forged bars of the TNTZ and TNTZ containing 0.89 mass% O (TNTZ-O) with a diameter of 5 mm and a length of 100 mm. For the vertebrectomy testing, ultrahigh molecular weight polyethylene (UHMWPE) test blocks were also used as simulating bone.

2.2 Compressive fatigue testing

Testing of the spinal implant assemblies was based on a simulated vertebrectomy model using a large gap between two UHMWPE test blocks based on American Society for Testing Materials (ASTM)-F1717. Each fatigue test was performed at a frequency of 5 Hz with a stress ratio, R = 0.1. The rod breakage was an indication of failure in this fatigue testing. The ASTM standard for the fatigue test indicates the run-out number of cycles (5×10^6 cycles). Therefore, the fatigue test was retained until failure or 5×10^6 cycles.

In addition, the fretted surfaces of the Ti–6Al–4V (Ti64) plugs were analyzed using a scanning electron microscopy (SEM) after the ASTM-F1717 tests. Electron probe micro-analyzer (EPMA) observations were also performed to enable analysis of the niobium (Nb) intensity within the fretted surfaces.

3. Results and discussion

3.1 Compressive fatigue testing

The maximum cyclic compressive load–the number of cycles to failure (S–N) curves obtained from the compressive fatigue testing of the Ti-based spinal construct using the TNTZ and TNTZ-O rods are shown in Fig. 1. The fatigue strength of TNTZ-O significantly increases compared to that of TNTZ. This result indicates that solid-solution strengthening by O improves the fatigue resistance of the TNTZ rod material.

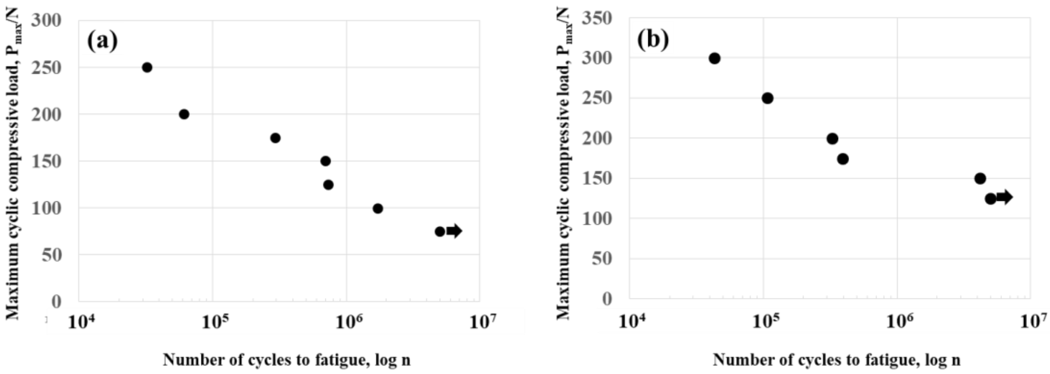

Fig. 1 Compressive fatigue test results for Ti-based spinal constructs containing (a) TNTZ and (b) TNTZ-O rods using an ASTM-F1717 model.

3.2 Observation at fretted surface

After the rod breakage in the ASTM-F1717 tests, the fretted surfaces of the Ti64 plugs were analyzed using both SEM and EPMA, as shown in Fig. 2. Particularly, large amount of Nb is clearly identified only on the fretted surface of the Ti64 plug against TNTZ rod, as shown in Fig. 2 (b). It is considered that the galled region in Fig.2 (a) is adhesive material detached from the TNTZ rod. Furthermore, this adhesive materials indicate that strong adhesion occurs between the Ti64 plug and TNTZ rod. While, in the case of the TNTZ-O rod, no Nb material is identified on the fretted surface of the Ti64 plug, as shown in Fig. 2 (d). It is also considered that solid-solution strengthening by O improves the plastic shear resistance of the TNTZ, which reduces the adhesion. This is because that adhesive materials are generally adhered from the softer material to the harder material.

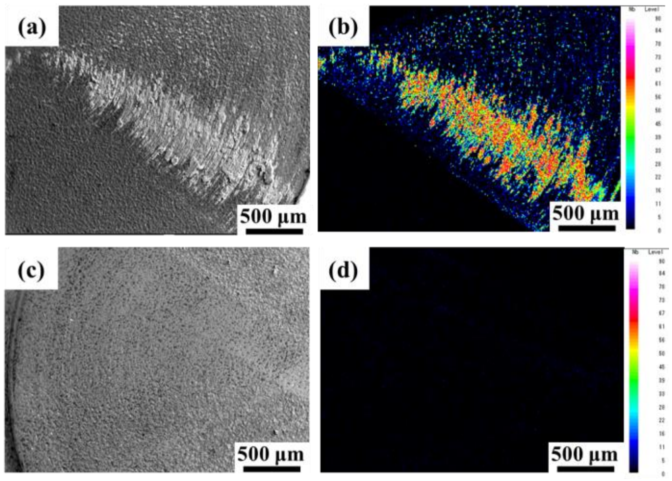

Fig. 2 SEM micrographs ((a) and (c)) and corresponding EPMA maps ((b) and (d)) of Nb on contacting surfaces of Ti64 plugs against (a) and (b) TNTZ and (c) and (d) TNTZ-O rods.

4. Summary

In this study, fatigue strengths of two Ti-based spinal constructs using TNTZ and TNTZ-O rods were evaluated according to the ASTM 1717 standard and analyzed. The primary findings of this study are the following:

1. The fatigue strength of TNTZ-O significantly increases compared to that of TNTZ. This result indicates that solid-solution strengthening by O improves the fatigue strength of the TNTZ rod material via improvement of plastic shear resistance.
2. It is considered that strong adhesion occurs between the Ti64 plug and TNTZ rod. While, in the case of the TNTZ-O rod, it is considered that solid-solution strengthening by O improves the plastic shear resistance of the TNTZ, which reduces the adhesion.