

# Fatigue Properties of Titanium Wires for Medical Applications

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The fatigue properties of commercially pure titanium, Ti-10mass%Zr alloy, and  $\beta$ -type Ti-14mass%Mo-3mass%Nb-1.5mass%Zr alloy wires with diameters in the range of 50-200  $\mu\text{m}$  for use as electrodes in a functional electrical stimulation system were investigated on the basis of rotating bending testing in 1 mass% lactic acid solution maintained at 310 K. An elution of metallic ions from the wires into 1 mass% lactic acid solution was suppressed at a very low level during fatigue testing. The fatigue strength of the wires was less than 50% of the tensile strength. The presence of the surface defects that were introduced during the cold drawing process of the wires might act as crack origins of the fatigue fracture. An optimization of the cold drawing process is needed to improve the fatigue properties of titanium wires.

**Keywords:** titanium wire, functional electrical stimulation, electrode, lactic acid solution, elution, fatigue strength, rotating bending fatigue testing.

## 1. Introduction

The present authors have developed a percutaneous intramuscular electrode for the functional electrical stimulation (FES) system<sup>1,2</sup>. The electrode was made from a helically coiled rope wound from 19 strands of hard drawn wires of austenitic stainless steel. The diameter of the wires was 25  $\mu\text{m}$ . In the percutaneous FES system, however, daily maintenance of the region around the lead exit sites is required in order to avoid infection; this is a burdensome to patients and their families. Therefore, a totally implantable system would be more desirable for FES<sup>3</sup>. The functional requirements of an electrode in a totally implantable FES system are that it should be more biocompatible and reliable than an electrode in a percutaneous FES system because its replacement is not as easy and it is expected to function for at least ten years after implantation.

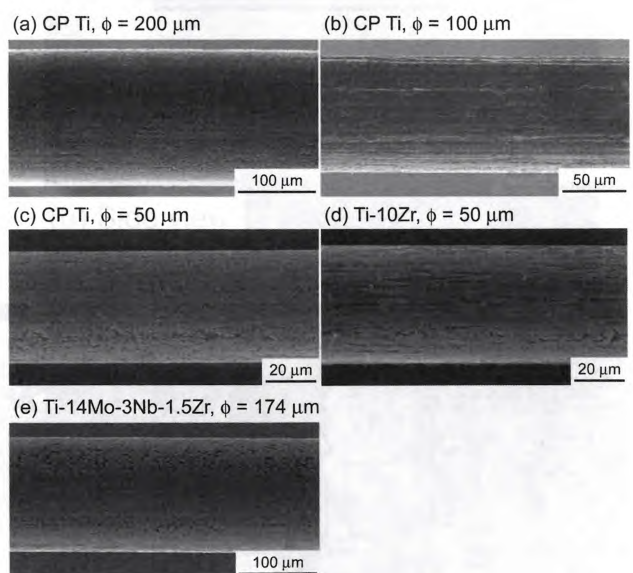
Titanium and its alloys have been widely used in dental and medical implants because of their excellent properties such as lightweight, corrosion resistance, strength-ductility balance and biocompatibility<sup>4</sup>. Therefore, titanium can potentially be used as a source material for a totally implantable FES electrode. The mechanical properties of fine-diameter wires made of titanium materials under biological conditions should be clarified in order to apply them to an FES electrode. In this study, the fatigue properties of cold drawn titanium wires in 1 mass% lactic acid solution at 310 K were investigated on the basis of rotating bending fatigue testing.

## 2. Experimental

Titanium wires made of commercially pure titanium (Nilaco, Tokyo, Japan), Ti-10mass%Zr alloy (Hiyama Rare-Metal Industry, Koga, Japan) or  $\beta$ -type Ti-14mass%Mo-3mass%Nb-1.5mass%Zr alloy<sup>5</sup> were used for fatigue testing; hereafter, these will be referred to as CP Ti, Ti-10Zr, and Ti-14Mo-3Nb-1.5Zr, respectively. The

**Table 1.** Diameter and tensile strength of titanium wires.

Type	Materials	Diameter, $\phi$ ( $\mu\text{m}$ )	Tensile Strength, $\sigma_U$ (MPa)
$\alpha$	CP Ti	200	450
$\alpha$	CP Ti	100	970
$\alpha$	CP Ti	50	880
$\alpha$	Ti-10Zr	50	1200
$\beta$	Ti-14Mo-3Nb-1.5Zr	174	1000



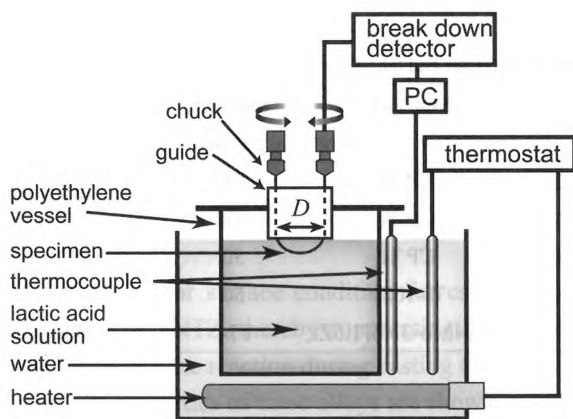
**Figure 1.** Side view of titanium wires. (a) CP Ti,  $\phi = 200 \mu\text{m}$ ; (b) CP Ti,  $\phi = 100 \mu\text{m}$ ; (c) CP Ti,  $\phi = 50 \mu\text{m}$ ; (d) Ti-10Zr,  $\phi = 50 \mu\text{m}$ ;

diameters and tensile strengths of the as-cold-drawn wires are summarized in Table 1. Figure 1 shows the side view of the wires used for fatigue testing in this study.

The fatigue life of the wire was evaluated using a dual-axle-driven rotating bending fatigue machine, of which schematic representation is shown in Fig. 2. A pair of axles were rotated in opposite directions, which led to repeated bending of the specimen wire. The rotation rate of the axles was fixed at 1000 rpm. The bending stress was varied by changing the distance between the two axles. This distance was varied from 10 mm to 70 mm. The values of the maximum bending stress ( $\sigma_B$ ) were roughly estimated from using the following equation:

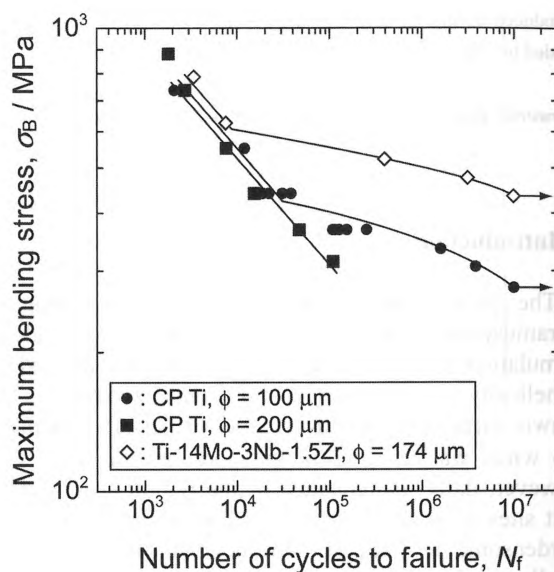
$$\sigma_B = E\phi / D \quad (1)$$

where  $E$  is Young's modulus for titanium materials,  $\phi$  is the diameter of the wire and  $D$  is the distance between the centerline of the two axles. Values of 110 GPa and 90 GPa were used as Young's modulus for the  $\alpha$ -type and  $\beta$ -type titanium materials, respectively. The fatigue testing was

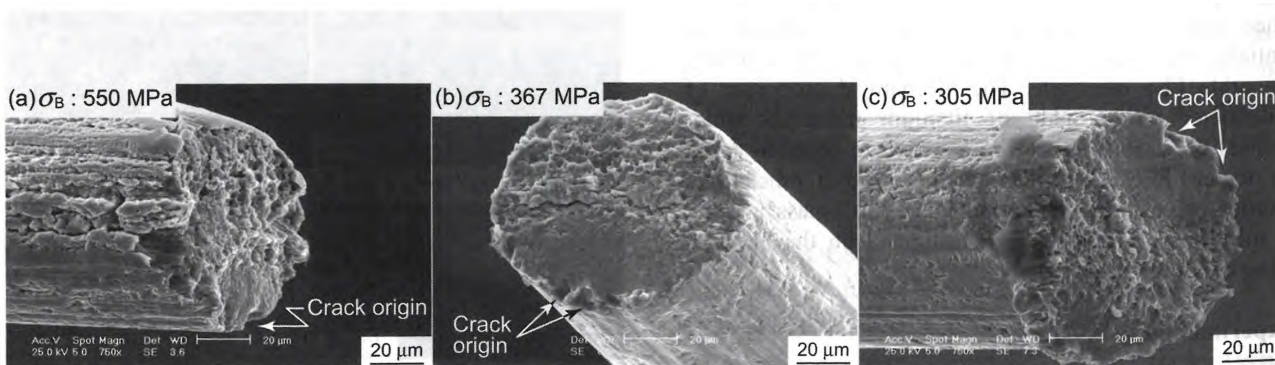


**Figure 2.** Schematic diagram of the rotating bending fatigue machine.

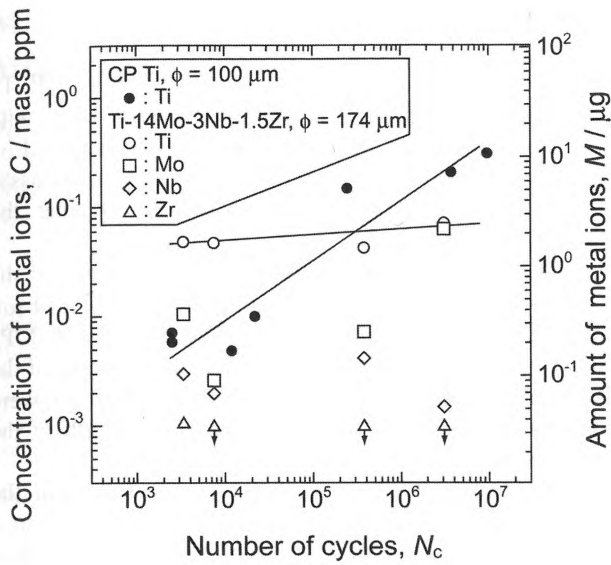
stopped when the specimen wire failed or the number of cycles reached  $10^7$  cycles. The curved part of the specimen wire was immersed in 1 mass% lactic acid solution maintained at 310 K with an initial pH of 2.2. The solution volume was 30 cm<sup>3</sup>. After fatigue testing, the fracture surface and the side surface of the wires were observed using a scanning electron microscope (SEM). The solution used for fatigue testing was filtered with a membrane filter made of polycarbonate with a pore size of 0.1  $\mu$ m. The metallic ion concentration of the filtrate was quantitatively determined on the basis of inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis.



**Figure 3.** Fatigue curves of the titanium wires in 1 mass% lactic acid solution maintained at 310 K.



**Figure 4.** Fracture surface of CP Ti wires with a diameter of 100  $\mu$ m after fatigue testing at a maximum bending stress of (a) 550 MPa, (b) 367 MPa, and (c) 305 MPa.

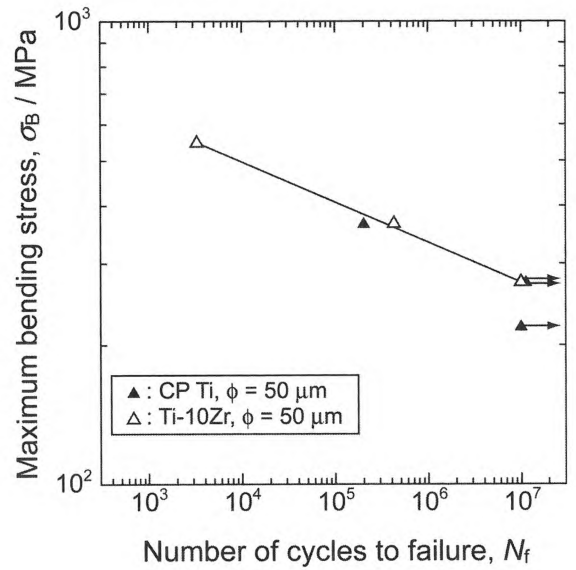


**Figure 5.** Change in the concentration of metal ions released from the wire with the fatigue cycle.

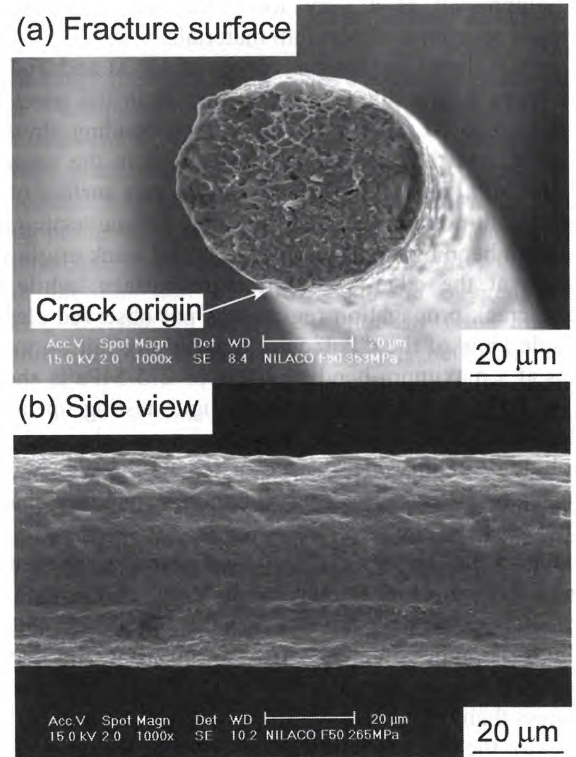
### 3. Results and discussion

The fatigue curves of CP Ti wires with diameters of 100  $\mu\text{m}$  and 200  $\mu\text{m}$  and Ti-14Mo-3Nb-1.5Zr alloy wire with a diameter of 174  $\mu\text{m}$  used in rotating bending fatigue testing are shown in Fig. 3. The arrowheads in the figure indicate that the specimen wire did not fail up to  $10^7$  cycles. No failure up to  $10^7$  cycles was observed for the CP Ti wire with a diameter of 100  $\mu\text{m}$  and the Ti-14Mo-3Nb-1.5Zr alloy wire at a maximum bending stress of 275 MPa and 435 MPa, respectively. Therefore, the fatigue strengths can be evaluated to be in the range of 275-306 MPa and 435-475 MPa for the CP Ti wire and the Ti-14Mo-3Nb-1.5Zr alloy wire, respectively.

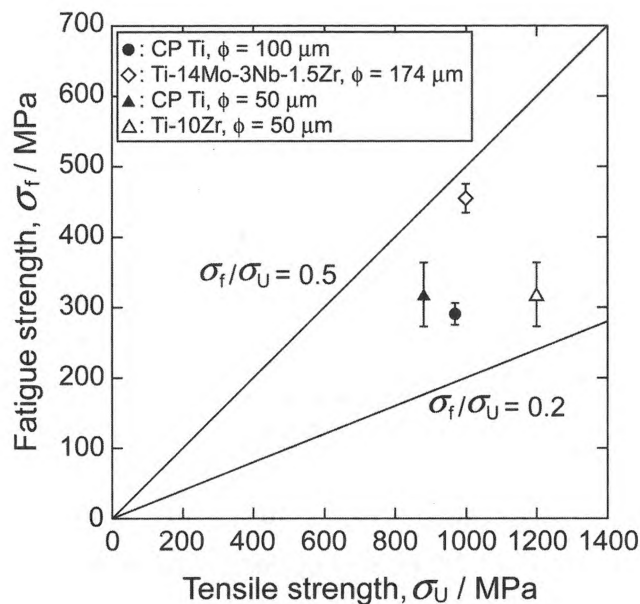
Figures 4 (a), (b), and (c) show the fracture surfaces of the CP Ti wire with a diameter of 100  $\mu\text{m}$  under a maximum bending stress of 550 MPa, 367 MPa, and 305 MPa, respectively. The fracture surface consists of two regions, viz., the fatigue crack propagation region and the final overload region<sup>6)</sup>. The crack origin was observed at the edge of the fracture surfaces. It is likely that the crack originated from the surface defects formed during the cold drawing process of the wire and then propagated inside the wire<sup>7)</sup>. The decrease in the cross section area of the wire led to the final overload failure. The fatigue crack propagation region for a maximum bending stress of 550 MPa cannot be observed as clearly as that for a lower maximum bending stress of 367 MPa or 305 MPa, which could cause a change in gradient of the fatigue curves at around  $10^4$  cycles, as shown in Fig. 3. Figure 5 shows the concentration of metallic ions released from the CP Ti wire with a diameter of 100  $\mu\text{m}$  and the Ti-14Mo-3Nb-1.5Zr alloy wire into the 1 mass% lactic acid solution as a function of the number of cycles. The concentration of zirconium ions was below the



**Figure 6.** Fatigue curves of the titanium wires with a diameter of 50  $\mu\text{m}$  in 1 mass% lactic acid solution maintained at 310 K.



**Figure 7.** (a) fracture surface and (b) side view of CP Ti wire with a diameter of 50  $\mu\text{m}$  after fatigue testing. The maximum bending stresses



**Figure 8.** Relationship between the tensile strength and the fatigue strength of titanium wires.

ICP-AES detection limit used in this study, which is indicated by arrowheads in Fig. 5. The metallic ion elution was suppressed at a very low level due to the high corrosion resistance of titanium materials.

Figure 6 shows the fatigue curves of CP Ti and Ti-10Zr alloy wires with a diameter of 50  $\mu\text{m}$ . Both the wires did not fail up to  $10^7$  cycles at a maximum bending stress of 275 MPa, and their fatigue strengths were in the range of 275-367 MPa. Figure 7 (a) shows the fracture surface of CP Ti wire with a diameter of 50  $\mu\text{m}$  after fatigue testing at a maximum bending stress of 367 MPa. The crack origin was detected at the edge of the fracture surface, while the fatigue crack propagation region was not observed clearly. The side view of the CP Ti wire that did not fail up to  $10^7$  cycles at a maximum bending stress of 275 MPa is shown in Fig. 7 (b). It is suggested that fatigue testing up to  $10^7$  cycles in 1 mass% lactic acid solution changed the morphology of the side surface of the CP Ti wire with a diameter of 50  $\mu\text{m}$ . The cause of the morphology change has not yet been clarified.

Figure 8 summarizes the relationship between the tensile strength ( $\sigma_U$ ) and the fatigue strength ( $\sigma_f$ ) of the titanium wires. It is empirically known that the fatigue strength of titanium is approximately 50% to 60% of the tensile strength. However, the values of  $\sigma_f/\sigma_U$  in the titanium wires were less than 0.5. As shown in Figs. 4 (a), (b), and (c) and Fig. 7 (a), the crack origin was observed at the edge of the fracture surface. The presence of the surface defects that were introduced during the cold drawing process might act as crack origins of the fatigue fracture and they appears to lower the value of  $\sigma_f/\sigma_U$ . Therefore, an optimization of the cold drawing process is needed to improve the fatigue properties of the titanium wires.

#### 4. Conclusion

The fatigue properties of the wires made of CP Ti, Ti-10Zr alloy and  $\beta$ -type Ti-14Mo-3Nb-1.5Zr alloy with diameters in the range of 50-200  $\mu\text{m}$  were investigated on the basis of rotating bending fatigue testing in 1 mass% lactic acid solution maintained at 310 K, yielding the following findings.

(1) The CP Ti wire with a diameter of 100  $\mu\text{m}$  and the Ti-14Mo-3Nb-1.5Zr alloy wire with a diameter of 174  $\mu\text{m}$  exhibited fatigue strengths in the range of 275-306 MPa and 435-475 MPa, respectively. The fatigue strengths of the CP Ti and the Ti-10Zr wires with a diameter of 50  $\mu\text{m}$  were in the range of 275-367 MPa. The fatigue strength of the wires was less than 50% of their tensile strength.

(2) An elution of the metallic ions released from the titanium wires during fatigue testing was suppressed at a very low level in 1 mass% lactic acid solution due to their high corrosion resistance.

(3) The crack origin was observed at the edge of the fracture surface of the titanium wires. The presence of the surface defects that were introduced during the cold drawing process might act as crack origins of the fatigue fracture. An optimization of the cold drawing process is needed in order to improve the fatigue properties of the titanium wires and to apply them to FES electrodes.

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