Fatigue Property of Ti-5Al-13Ta Alloy Dental Castings in 0.9% NaCl Solution

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The purpose of this study was to evaluate the fatigue property of Ti-5Al-13Ta alloy castings for dental application since dental prostheses are used under repetitive stress condition. Dumbbell-shaped cast specimens were prepared with a centrifugal casting machine and a magnesia-based mold material. Fatigue test was performed at 310 K in 0.9% NaCl solution under repetitive loading condition with the maximum cycles at 10⁷. As a result, fatigue limit of Ti-5Al-13Ta alloy castings in NaCl solution was about 220 MPa, which was higher than those of CP-Ti, Ti-6Al-4V and Ti-6Al-7Nb alloys, previously reported. Clear striation was observed at the crack propagation area on the fracture surface. The ratio of fatigue limit to UTS was suggested to be 30% for Ti-5Al-13Ta alloy castings; this value was higher than those for Ti-6Al-4V and Ti-6Al-7Nb alloys. It was concluded that Ti-5Al-13Ta alloy castings showed good fatigue property in 0.9% NaCl solution as an α + β high-strength titanium alloy for dental prostheses.

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1. Introduction

Commercially pure titanium (CP-Ti) has been used as a dental casting material because of its excellent biocompatibility₁,₂ however, it has disadvantages of low strength, difficulty in polishing, and poor wear resistance.³ To expand the dental application of titanium, it is required to improve the mechanical property of CP-Ti, because CP-Ti shows relatively low strength. Required tensile strength for CP-Ti grade 4, which exhibits highest strength among all grades of CP-Ti, is 550 MPa,⁴ while those for α + β high-strength titanium alloys of Ti-6Al-4V and Ti-6Al-7Nb are 860⁵ and 900 MPa,⁶ respectively. Consequently, these alloys have been introduced to dental casting,⁷ especially for high-stress applications like fixed prostheses and removable partial dentures. Since vanadium was reported to be citotoxic,⁸ Ti-6Al-4V alloy has been replaced by Ti-6Al-7Nb alloy, which was developed for orthopedic application as a wrought material.⁹

Niobium in Ti-6Al-7Nb alloy is an element in the group 5 in the periodic table and shows β-stabilizing effect in Ti-Nb binary system like vanadium. It was reported that Ti-6Al-7Nb alloy castings showed slightly lower strength and about 40% higher elongation than those of Ti-6Al-4V alloy castings in tensile test.¹⁰ They also showed excellent corrosion resistance,¹⁰ comparable castability¹¹ and wear resistance,¹² therefore, it has been increasingly used in clinical dental treatment.¹²,¹³

Tantalum is another element in the periodic group 5, and it is known to show excellent biocompatibility¹⁴,¹⁵ as well as to work as a β-stabilizer.¹⁶ In a previous study by the authors, Ti-5Al-13Ta alloy castings showed slightly less strength and much larger elongation than those of Ti-6Al-7Nb alloy castings in tensile test; the mechanical property was between those of CP-Ti and Ti-6Al-7Nb alloy castings.¹⁷ They also showed excellent corrosion resistance similar to CP-Ti, Ti-6Al-4V alloy and Ti-6Al-7Nb alloy, and it was evaluated to be suitable alloy for dental casting.¹⁷

Since medical and dental prostheses are used under repetitive stress condition for years, fatigue property is an important property to apply biomedical materials clinically.¹⁸⁻²¹ The fatigue fracture is a phenomenon occurring by repetitive stress at which the material does not fracture in a static condition. It is important to investigate the fatigue property in a corrosive environment,²²⁻²⁴ simulating the condition in which dental prostheses are used. The authors have been reported on the corrosion fatigue characteristics of CP-Ti, Ti-6Al-4V alloy, and Ti-6Al-7Nb alloy dental castings,²⁵ however, there has been no paper on the property of Ti-5Al-13Ta alloy. Therefore, fatigue property of Ti-5Al-13Ta alloy castings in 0.9% NaCl solution was investigated in comparison with those of CP-Ti, Ti-6Al-4V alloy, and Ti-6Al-7Nb alloy castings.

2. Materials and Methods

2.1 Specimens preparation

High-purity titanium (>99.8%, TB-270, Toho Technical Service, Japan), aluminum (99.99%, Hirano Seizaemon Shoten, Japan), and tantalum (99.9%, Hirano Seizaemon Shoten, Japan) were melted on a water-cooled copper crucible in an argon arc melting furnace to make Ti-5Al-13Ta alloy ingots for castings. Each ingot was turned over and remelted five times to ensure chemical homogeneity. Each ingot weighed approximately 30 g. Wax patterns were invested with a magnesium-based mold material (Selevest-CEB, Selec, Japan) to make the molds for castings. The configuration of the pattern was dumbbell-shaped: 3.0 mm in diameter and 15 mm in length at the parallel part, and 6.0 mm in diameter and 10 mm in length at the grip part. Specimens were cast with an argon-arc centrifugal casting machine (Ticast Super-R, Selec, Japan). The specimens were water-quenched at room temperature with the molds few minutes after casting, then the specimen surfaces were cleaned by sandblasting. No heat treatment was applied. The specimen surface of the parallel part was polished with #600 SiC paper.
2.2 Fatigue test in 0.9% NaCl solution

Fatigue test was carried out with a servo-hydraulic testing machine (Servopulser EHF-FB1, Shimadzu, Japan) in 0.9% NaCl solution. A corrosion bath, shown in Fig. 1, in a thermostatic chamber was used for the corrosion fatigue condition. The temperature of the testing part including corrosion bath and the solution was maintained at 310 K.

The specimens were subjected to repetitive loading condition at the frequency of 10 Hz in tension-tension mode with sine-waved load. The total number of the specimens was 20. The minimum load was set at 0.1 kN, and the maximum load was set at a value appropriate to the stress condition. Fatigue life was defined as the cycles of the specimen fracture. The number of maximum cycles for the fatigue test was set at $10^7$ cycles in this study, when the test was stopped. Fatigue limit was determined based on the maximum stress that the metal specimen could withstand for an infinitely large number of cycles with 50% probability of failure. With respect to the ion release in the fatigue test, no compositional metal ions were detected. The concentrations of titanium, aluminum, and tantalum was under the detective limit of the ICP spectrometer.

3. Results

3.1 Fatigue property in 0.9% NaCl solution

Maximum stress-fatigue life relation of Ti-5Al-13Ta alloy dental castings in 0.9% NaCl solution is shown in Fig. 2 in comparison with those of CP-Ti, Ti-6Al-4V, and Ti-6Al-7Nb alloy castings previously reported. With respect to the ion release in the fatigue test, no compositional metal ions were detected. The concentrations of titanium, aluminum, and tantalum was under the detective limit of the ICP spectrometer.

4. Discussion

One of the representative high-strength titanium alloy types is $\alpha + \beta$ type titanium alloy. Since the compositions of
main $\alpha + \beta$ high-strength titanium alloys, Ti-6Al-4V and Ti-6Al-7Nb, were expressed as Ti-10.2Al-3.6X in mol% (X: elements in the group 5), the composition of Ti-Al-Ta alloy was determined as Ti-5Al-13Ta in mass%. Tantalum belongs to the group 5 in the periodic table as vanadium and niobium and works as a $\beta$-stabilizing element in place of vanadium or niobium to provide a desirable $\alpha + \beta$ two-phase structure with aluminum, an $\alpha$-stabilizer. In addition, Tantalum has been used as a surgical implant material because of its high corrosion resistance and biocompatibility. The ultimate tensile strength (UTS) of Ti-5Al-13Ta alloy dental castings was reported as 771 MPa, which was higher than that of CP-Ti, 619 MPa, and slightly lower than that of Ti-6Al-7Nb alloy, 815 MPa. Consequently, it was suggested that this alloy was suitable to dental casting with its favorable mechanical and chemical properties.

Since metallic materials like steels and titanium alloys generally show fatigue phenomena under repetitive stress condition, fatigue property is an important factor to apply titanium alloys clinically. The author has previously examined the corrosion fatigue property of CP-Ti, Ti-6Al-4V alloy, and Ti-6Al-7Nb alloy dental castings as shown in Fig. 2. As a result, it was suggested that the ratio of fatigue limit to UTS in designing dental prostheses was 40% for CP-Ti and 20% for Ti-6Al-4V and Ti-6Al-7Nb alloys. From the data reported previously, the fatigue limits of CP-Ti and Ti-6Al-4V alloy castings were estimated to be around 170 MPa, while that of Ti-6Al-7Nb alloy was slightly high, approximately 180 MPa, in 0.9% NaCl solution. In this study, the fatigue limit of Ti-5Al-13Ta alloy castings was estimated to be 220 MPa, which was considerably higher in 0.9% NaCl solution than those of CP-Ti, Ti-6Al-4V alloy, and Ti-6Al-7Nb alloy, although the UTS of Ti-5Al-13Ta was lower than those of Ti-6Al-4V and Ti-6Al-7Nb alloys.

It is known that the tensile strength of a material has a close relation to the fatigue strength, and that the elongation to fracture is also correlated with it concerning the crack propagation. To evaluate the influence of the tensile strength related to ductility, stress concentration is generated at the site. This may lead to crack initiation. On the other hand, the surface of titanium alloys is covered with stable passive film of titanium oxide, which is the main reason for their superior corrosion resistance and biocompatibility. In this study, the fatigue limit of Ti-5Al-13Ta alloy castings in NaCl solution was higher than those of Ti-6Al-4V and Ti-6Al-7Nb alloys, which was thought to be an advantage for the material for dental prostheses.

5. Conclusions

Fatigue property of Ti-5Al-13Ta alloy castings in 0.9% NaCl solution was investigated and the following conclusions were drawn:

(1) Fatigue life of Ti-5Al-13Ta alloy castings decreased with increasing maximum stress.

(2) Fatigue limit of Ti-5Al-13Ta alloy castings in 0.9% NaCl solution, about 220 MPa, was higher than those of CP-Ti, Ti-6Al-4V, and Ti-6Al-7Nb alloys.

(3) No compositional metal ions were detected from the corrosive solution after the fatigue test of Ti-5Al-13Ta alloy castings.

(4) Clear striation was observed at the crack propagation area in the fracture surface of Ti-5Al-13Ta alloy castings.

(5) The ratio of fatigue limit to UTS in designing dental prostheses was suggested to be 30% for Ti-5Al-13Ta alloy castings.

REFERENCES