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Wear behavior of tetragonal zirconia polycrystal vs. titanium and titanium alloy

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Short title: Wear behavior of TZP vs. Ti

Abstract

The aim of this study was to clarify the influence of tetragonal zirconia polycrystal (TZP) on the two-body wear behavior of titanium (Ti). Two-body wear tests were performed using TZP, two grades of cp-Ti or Ti alloy in distilled water, and the cross-sectional area of worn surfaces was measured to evaluate the wear behavior. In addition, the surface hardness and coefficient of friction were determined and an electron probe microanalysis performed to investigate the underlying mechanism of wear. The hardness of TZP was much greater than that Ti. The coefficient of friction between Ti and Ti showed a higher value than the Ti/TZP combination. Ti was susceptible to wear by both TZP and Ti than TZP, indicating that the mechanism of wear between TZP and Ti was abrasive wear, whereas that between Ti and Ti was adhesive wear. No remarkable difference in amount of wear in Ti was observed between with TZP and Ti as the opposite material, despite the hardness value of Ti being much smaller than that of TZP.

Key words: two-body wear, zirconia, TZP, titanium, coefficient of friction, adhesive wear

1. Introduction

Zirconia ceramics, in particular, tetragonal zirconia polycrystal (TZP) are widely used in the biomedical field as materials for prosthetic devices due to their superior mechanical, chemical and aesthetic properties. Used extensively for total hip replacement, TZP has now also become a prevalent biomaterial in dentistry, as for example, in the fabrication of bridges and abutments for dental implants [1-3].

Clinically, ceramic abutments to support single dental implants have proved successful in the anterior region of the mouth. The introduction of TZP implant abutments, allowing individualization by milling, has provided new opportunities for achieving good esthetic results in single-tooth implant restorations [4]. These abutments are distinguished by their tooth-matched color, good tissue compatibility, nontoxicity and intrasulcular adaptability. One of the most frequently used custom abutments in the anterior tooth area is the custom TZP abutment designed using computer-aided design and manufacturing (CAD/CAM) technology [5-7].

A number of specific problems with transmucosal implant-abutment systems have been pointed out, including a micro-gap between the implant and the abutment, abutment screw loosening, consecutive fatigue and wear at the interface [8]. Such problems can lead to plaque retention at the interface, resulting in clinical sequelae such as bone loss, peri-implantitis, and potential loss of osseointegration [9-11]. Screw loosening is believed to result from loss of contact between the mating threads through wear of the original surfaces [12, 13]. Therefore, we believe that clinicians should consider wear of retaining screws as well as total hip replacement a serious issue.

When TZP is used as an abutment material and total hip replacement, it comes into direct contact with the titanium of the implant. This has raised serious concern, as numerous differences in hardness are recognized between TZP and titanium, and subsequent wear may lead to metallosis, which can cause loosening between the implant abutment and implant body and metal allergy originating in metal-wear debris.[14-17]

In our previous study, we estimated wear behavior between TZP and titanium based on depth of wear in the profile of worn surfaces.[18] However, we were unable to precisely evaluate the amount of wear from depth of wear alone, as amount of wear is influenced not only by depth, but width of wear, too.

Accordingly, the aim of the present study was to clarify two-body wear behavior by evaluating the cross-sectional area of worn surfaces using TZP, cp-titanium (Ti, grades 2 and 4) and titanium alloy (Ti alloy, Ti-6Al-4V) in distilled water. In addition, the coefficient of friction between TZP and Ti alloy, surface roughness, surface hardness, optical microscopic observation and electron probe micro-analysis were also carried out to elucidate the underlying mechanism of wear.

2. Experimental details

2.1 Specimen preparation

Tetragonal zirconia polycrystal (3 mol% yttria-stabilized, Tosoh, Tokyo, Japan), commercially pure titanium (cp-Ti, grades 2 and 4, Tokyo Titanium, Saitama, Japan) and titanium alloy (Ti-alloy, Ti-6Al-4V, Tokyo Titanium, Saitama, Japan) were used, as shown in Table 1.

Disks of 13 mm in diameter and 1 mm in thickness were prepared for measurement of surface roughness, hardness and wear; lower specimens were prepared for the friction test and wear test as described later. One end of each cylinder (10 mm in length and 5 mm in diameter with a radius of curvature of 5 mm) was used for the friction and wear tests using a CAD/CAM machine (DENTAL CAD/CAM GN-1, GC, Tokyo, Japan). These specimens were finally polished with 6-μm diamond pastes.

2.2 Measurement of surface roughness and hardness

Arithmetic mean roughness (Ra) was measured using a surface profilometer (Surfcom 130A, Tokyo Seimitsu, Tokyo, Japan) with a measuring length of 4 mm and cut-off value of 0.8 mm.

Vickers hardness (Hv) was measured using a hardness tester (MVK-E, Akashi, Akashi, Japan) under conditions of 4.9 N/20s for TZP and 1.96 N/20s for cp-Ti and Ti alloy.

2.3 Measurement of coefficient of friction

The coefficient of friction was determined in accordance with ASTM G133-05, using a pin-on-disk tribometer (Nanovea TRB, Irvine, CA, USA). The following conditions were applied: Load, 1.0 N; Duration of test, 5 min; Rotational rate, 30 rpm; Lubricant, distilled water; Atmosphere, air: Temperature, 23°C (room); Humidity, 35%. Three specimens were used for each pair of TZP/TZP, Ti-4/Ti-4 and TZP/Ti-4.

2.4 Wear testing

Schematics of the wear tests are shown in Figure 1. As seen in Figure 1a, each upper specimen was moved back and forth on the lower specimen over a distance of 3 mm for 5,000 or 30,000 cycles at a speed of 90 cycles/min and with a vertical load of 10 N. The test was carried out at room temperature with distilled water circulated through a water chamber in order to remove abrasion debris.

After 5,000 or 30,000 cycles, the wear profile of the lower specimen was recorded at a right angle to the direction of movement of the upper specimen using a surface profilometer (Surfcom 130A, Tokyo Seimitsu, Tokyo, Japan). From this profile, the wear tendency of the specimen was estimated with reference to the cross-sectional area (S) of the chart (Figure 1b).

Five specimens were used for each combination. Ti-2 was used as only the lower specimen against TZP.

The worn surfaces of the lower specimens were also observed using an optical microscope (BX51, Olympus, Tokyo, Japan).

2.5 Electron probe micro-analysis

An X-ray image analysis of the lower specimens was performed to identify abraded particles that had adhered to the lower specimens using an electron probe micro-analyzer (EPMA, JXA-8200, JEOL, Tokyo, Japan).

2.6 Statistical analysis

For the statistical analysis, an analysis of variance (ANOVA) was used for the coefficient of friction and cross-sectional area in the wear test, followed by the Scheffe test for a *post hoc* comparison between groups.

3. Results

3.1 Surface roughness and hardness

The surface roughness and Hv of the specimens used in this study are shown in Table 2. All specimens showed mirror-like surfaces with less than 0.1 μm of Ra. The hardness of TZP was remarkably high (Hv=1356), whereas that of cp-Ti and Ti alloy was low, with an Hv of 125, 177 and 256 for Ti-2, Ti-4 and Ti-6Al-4V, respectively.

3.2 Coefficient of friction

The coefficient of friction between Ti-4/Ti was the highest ($p<0.05$). No significant differences were observed in the coefficient of friction between TZP/TZP and TZP/Ti-4 (p>

0.05, Figure 2).

3.3 Two-body wear

Typical OM images of worn surfaces in lower specimens after 30,000 cycles against upper specimens of TZP and Ti-4 are shown in Figure 3. When TZP was used as the upper specimen (Figure 3-a), large craters originating in wear were observed in Ti-4 and Ti-alloy, but were absent in TZP. When Ti-4 was used as the upper specimen (Figure 3-b), very similar craters were observed, as shown in Figure3-a. However, the peripheral morphology of the craters was different between TZP (a) and Ti-4 (b) as the upper specimen. A very sharp morphology was recognized when TZP was used as the upper specimen (arrows in Figure 3-a). When Ti-4 was used as the upper specimen (arrows in Figure 3-b), irregular shapes were observed, suggesting that some substances which had adhered had been pulled off.

Figure 4 shows the cross-sectional area of the lower specimens against various upper specimens under the 2-body wear test. The ANOVA revealed significant differences in cross-sectional area among both upper specimens and lower specimens ($p<0.05$). No remarkable wear was recognized at after 5,000 cycles when TZP was used as both the upper and lower specimen. When TZP was used as the upper specimen, after 30,000 cycles Ti-2 showed the largest cross-sectional area among the specimens, closely followed by Ti-4 and Ti alloy, whereas TZP showed quite a small cross-sectional area. When Ti-4 or Ti alloy were used as the upper specimen, the cross-sectional area of the worn surfaces showed a similar tendency, with a very low wear of TZP. The cp-Ti (Ti2 and Ti-4) and Ti alloy were partially less susceptible to wear by TZP than by titanium (Ti2, Ti-4 and Ti-alloy). On the other hand, TZP was less susceptible to wear by either material, especially by Ti as upper material. No remarkable differences in the cross-sectional areas of Ti-4 and Ti-alloy were observed when TZP and Ti (Ti-4 and Ti-alloy) were used as upper specimens ($p>0.05$), despite the hardness of cp-titanium and titanium being much smaller than that of TZP.

3.4 Electron probe micro-analysis

Characteristic X-ray images of the worn surface on the lower TZP specimen against Ti-alloy (Ti-6Al-4V) as the upper specimen are shown in Figure 5. Particles of Al and V were identified as abraded particles (arrows) that had adhered to lower specimens of TZP. Figure.6 shows characteristic X-ray images of the worn surface on the lower Ti-4 specimen against Ti-alloy (Ti-6Al-4V) as the upper specimen. Particles of Al and V originating in the upper specimen were detected adhering to the lower Ti-4 specimen (arrows).

4. Discussion

The aim of this study was to clarify the influence of TZP on the two-body wear behavior of titanium, as severe wear of titanium implants is expected when TZP is used as an abutment material due to large differences in hardness between the two types of material. The results showed no remarkable difference in amount of wear when titanium was exposed to TZP or Ti in the upper specimens, despite the hardness of titanium being much less than that of TZP. This result was quite different from that which was expected.

We evaluated the cross-sectional area of lower specimens subjected to wear against upper specimens in order to estimate wear tendencies, as opposed to depth of wear, which was the objective of our previous study [18].We believe that cross-sectional area is more suitable than depth of wear for estimation of wear behavior between TZP and titanium, as contact between the upper and lower specimens will mean that the upper specimen is also subjected to wear, which will affect depth of wear in the lower specimen, especially with the combination of titanium and titanium due to the type of wear mechanism that is involved, which we discuss later. This suggests the need for further study to identify more accurate methods of evaluating sliding wear.

The wear tests were not carried out in physiological solutions, because the deterioration of organic substances in physiological solutions is feared during test periods. In addition, we believe that it is predicable in wear behavior in distilled water instead of physiological solutions because TZP and titanium may not to be influenced by the inorganic substances in physiological solutions due to their superior corrosion resistance and stable properties. Test solution was circulated through a water chamber in order to remove abrasion debris.

The wear mechanisms observed in this study were mainly abrasive wear and adhesive wear [19]. Abrasive wear occurs when a hard, rough surface slides across a softer surface. The common analogy is that of material being removed with abrasive paper [20-22]. On the other hand, adhesive wear occurs when two bodies slide over each other, or are pressed into one another, which promotes material transfer between the two surfaces. In initial contact, fragments of one surface are pulled off and adhere to the other, due to the strong adhesive interaction between two surfaces with similar physicochemical properties such as metal to metal [23,24].

In this study, titanium (cp-Ti and Ti-alloy) was susceptible to wear by TZP. The hardness of TZP was markedly higher (Hv=1356) than that of cp-Ti or Ti alloy, which showed low Hv values of 125, 177 and 256 for Ti-2, Ti-4 and Ti-6Al-4V, respectively. This indicates that the operating mechanism of wear between the titanium and the TZP was abrasive wear due to the ultra-hardness of the TZP.

The cp-Ti and Ti-alloy were also susceptible to wear by titanium, which had a similarly low hardness compared to TZP, suggesting that the operating mechanism of wear here was adhesive wear. This supposition is supported by the results of the coefficient of friction. The coefficient of friction between Ti-4 and Ti-4 showed a higher value than the Ti4/TZP combination, showing that a strong adhesive interaction had occurred. This is also supported by the worn surfaces observed with titanium against titanium, in which an irregular morphology had resulted from eroded particles from the upper specimens adhering to the lower specimens (Figure3-b, arrow).

In the EPMA analysis, Al and V were detected on both TZP and Ti-4 surfaces in the lower specimens when Ti-alloy (Ti-6Al-4V) was used as the upper specimen. These results showed that worn particles of Ti-6Al-4V alloy had attached to the opposite specimens, which would represent a hazard to health from the presence of V in those particles. On the other hand, the TZP was less susceptible to wear by either TZP or titanium. These results suggest that in order to successfully avoid metallosis originating in worn particles, it would be better to carry out metal-free restoration using TZP in implant prostheses.

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Table 1 Materials Used in This Study

Classification	Code
3 mol% yttria-stabilized tetragonal zirconia polycrystals	TZP
cp-titanium grade 2	Ti-2
cp-titanium grade 4	Ti-4
Titanim alloy (Ti-6Al-4V)	Ti-alloy

Table 2 Surface Roughness（Ra, μm) and Hardness（Hv）

Specimen	Surface roughness	Hardness
TZP	0.067(0.005)	1356 (14)
Ti-2	0.056(0.004)	125 (2)
Ti-4	0.065(0.006)	177 (4)
Ti-alloy	0.069(0.003)	256 (14)

( ): SD

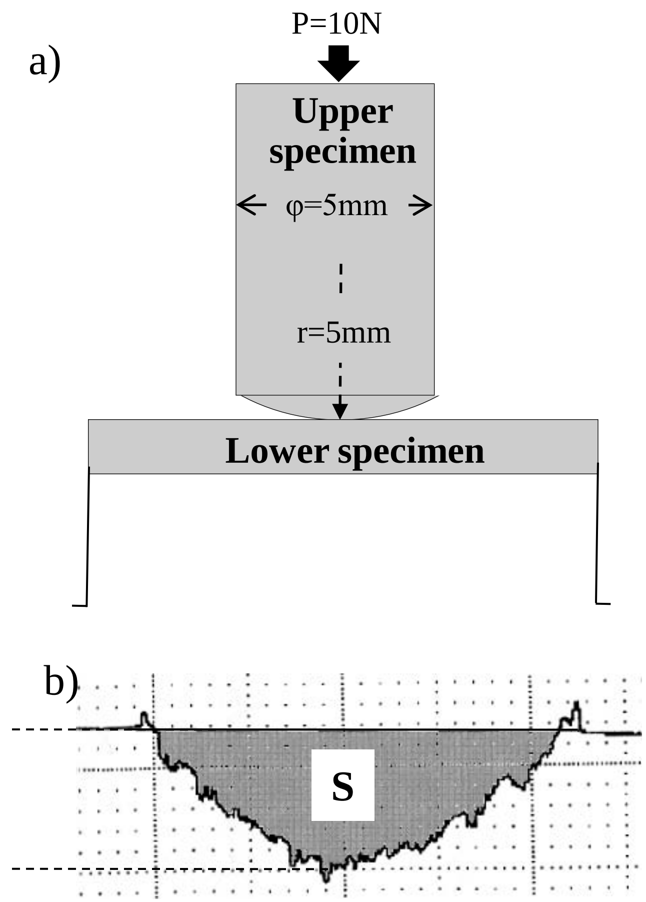

Fig 1 Schematic illustrations of the wear test (a), and the cross section of the worn specimen (b), S: cross-sectional area

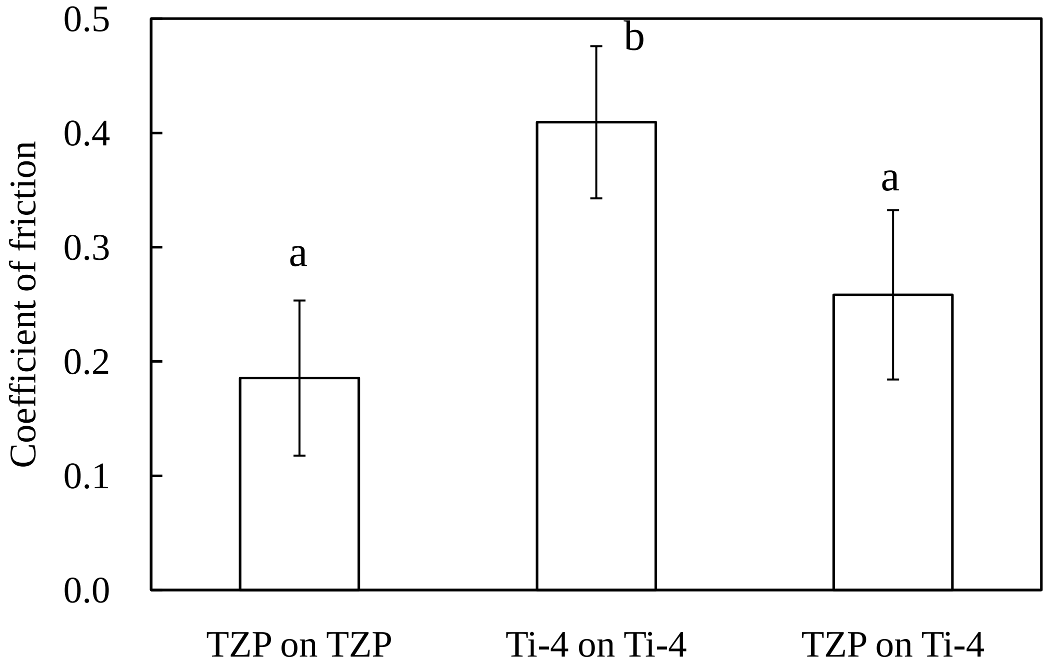

Fig. 2　Coefficient of friction between TZP/TZP, Ti-4/Ti-4 and TZP/Ti-4. Identical letters indicate no significant difference (p>0.05).

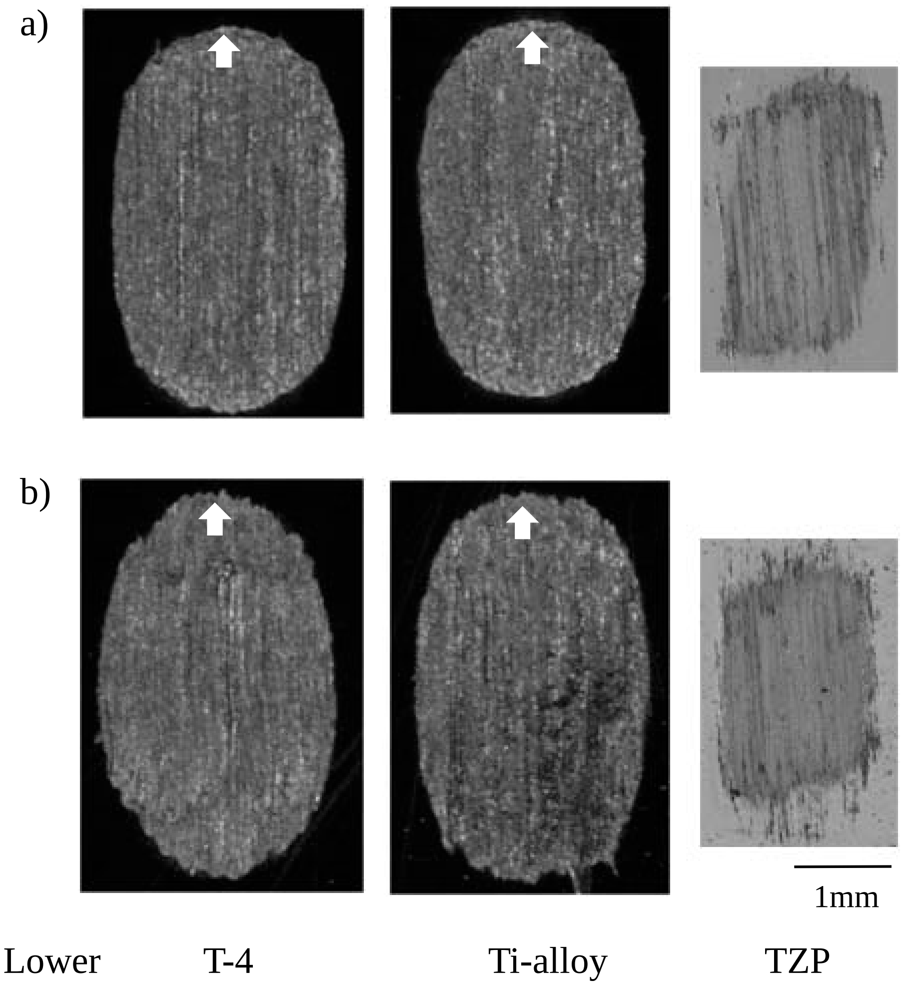

Fig.3 Typical OM images of worn surfaces of lower specimens at 30,000 cycles against upper specimens of a) TZP and b) Ti-4.

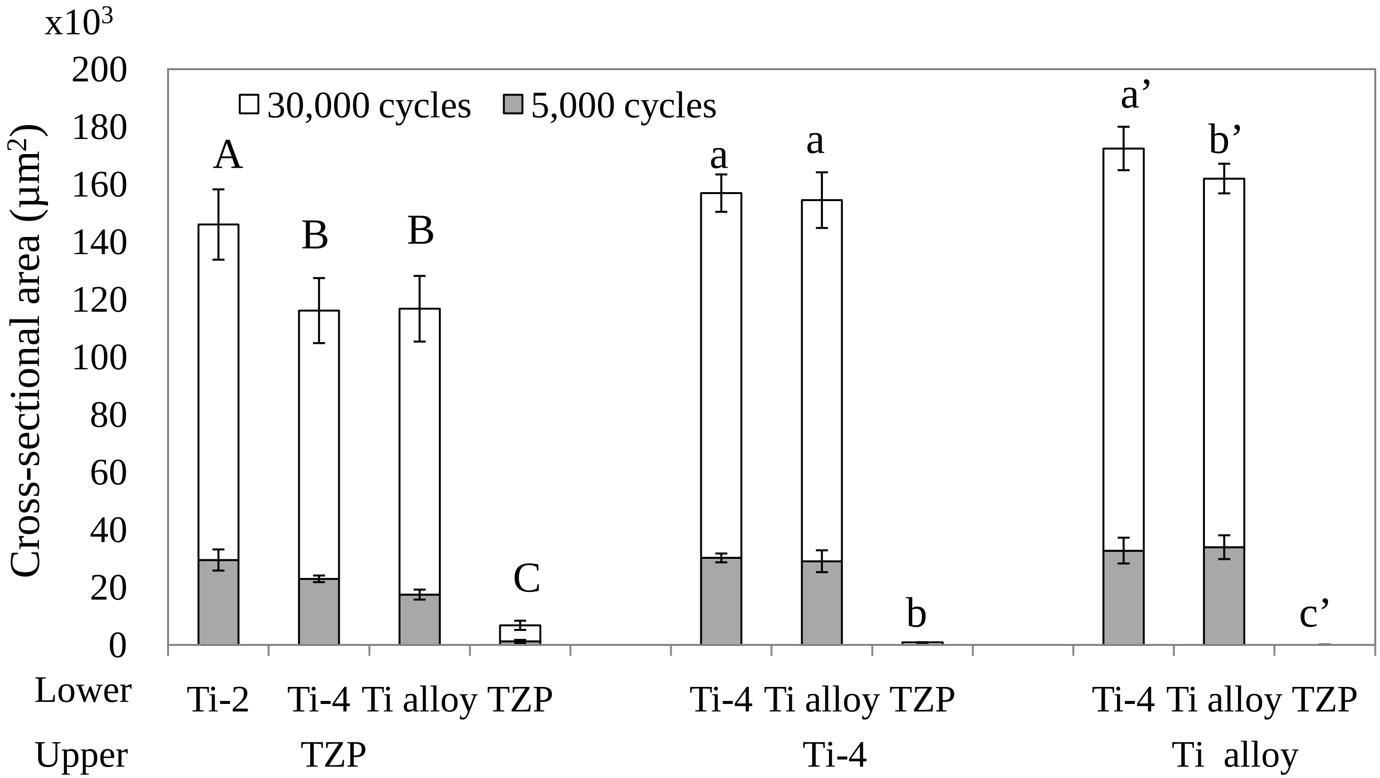

Fig.4 Cross-sectional area of lower specimens against various upper specimens under 2-body wear test. Identical letters indicate no significant difference ($p>0.05$).

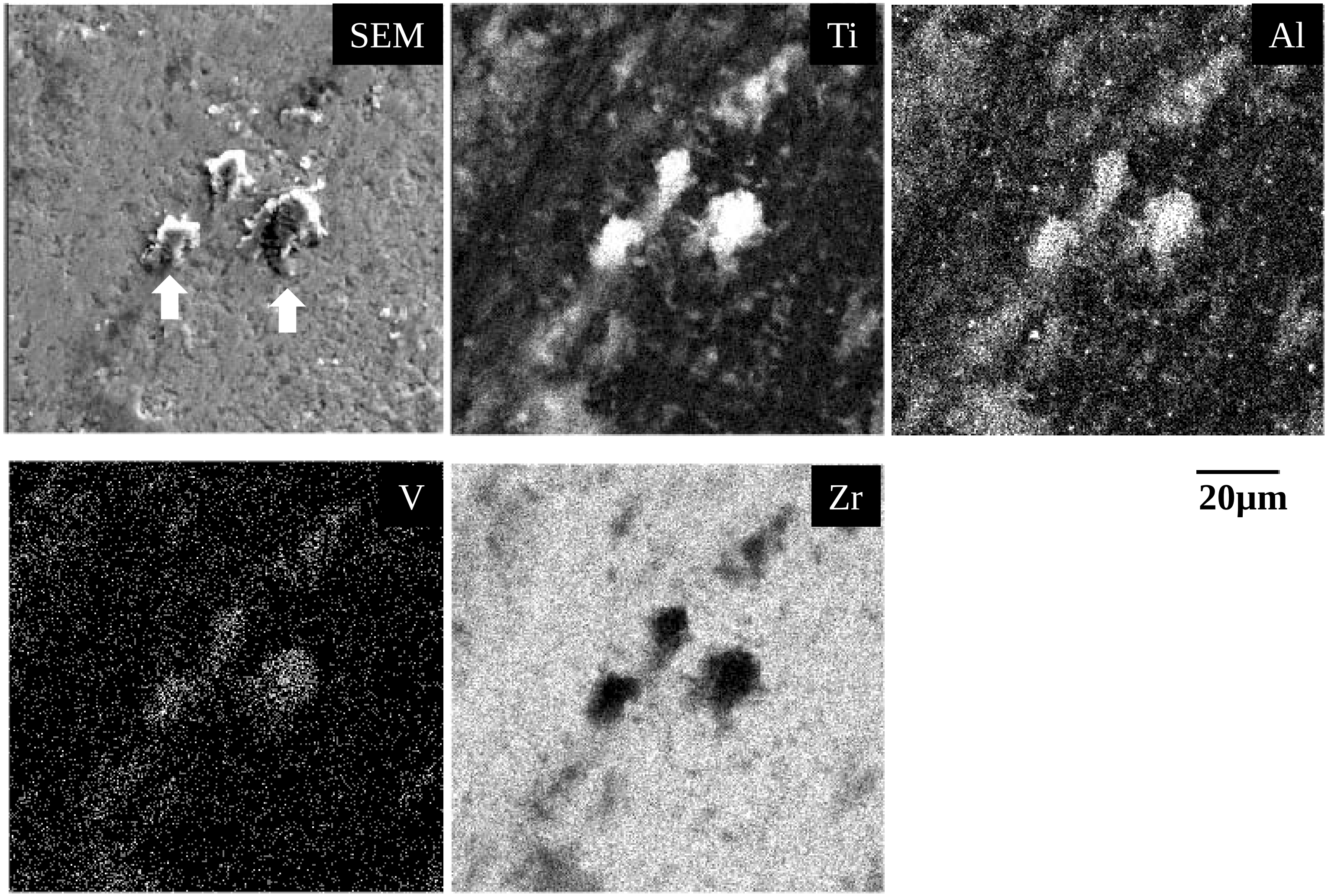

Fig. 5　X-ray image analysis of lower TZP specimen when Ti-alloy（Ti-6Al-4V) was used as an upper specimen.

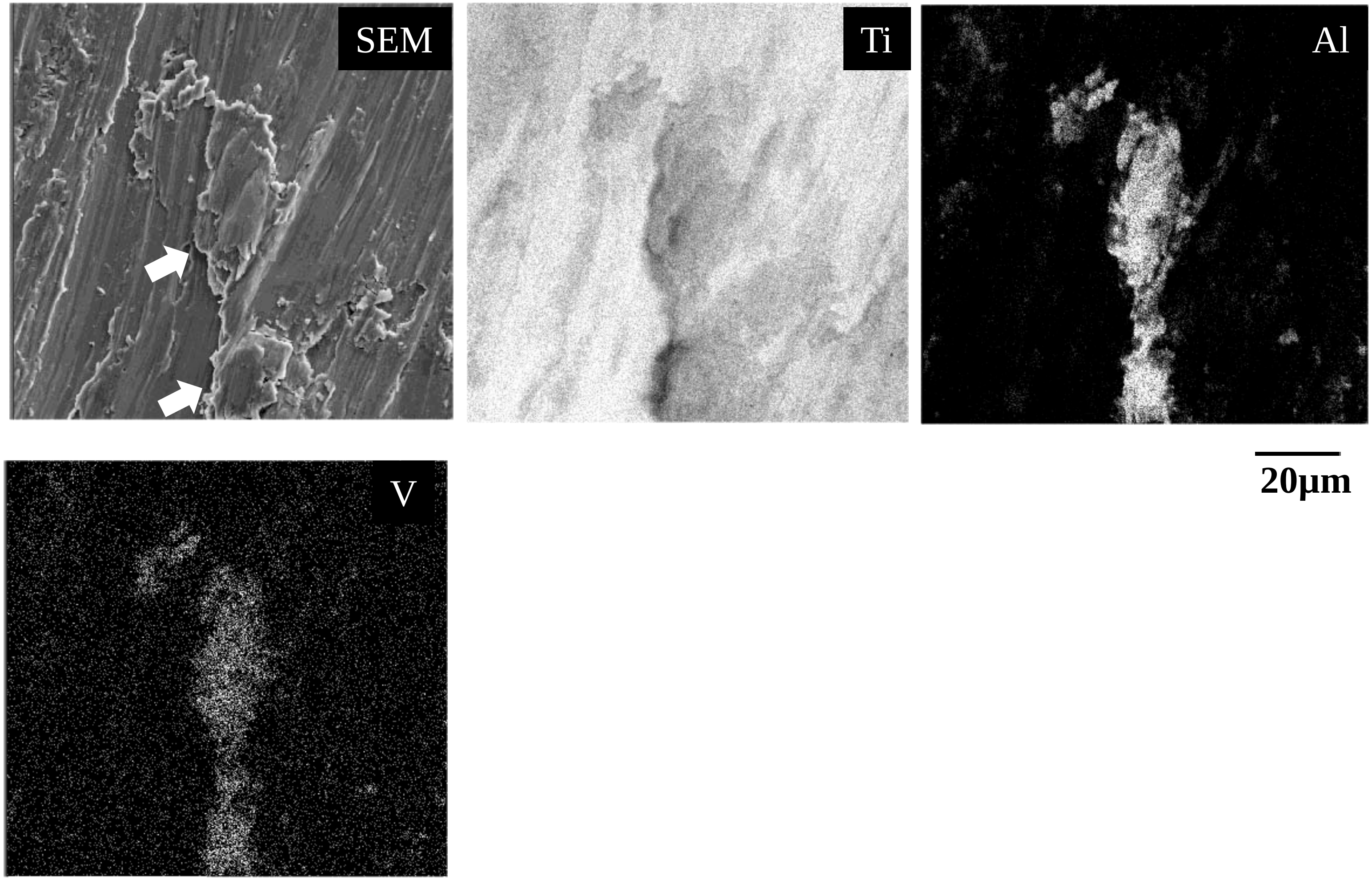

Fig. 6　X-ray image analysis of lower Ti-4 specimen when Ti-alloy（Ti-6Al-4V) was used as an upper specimen.