PROSIDING SNTTM XXIII 2025
Volume 23, No. 1, Tahun 2025, 9 Oktober 2025
e-ISSN 2623-0313
p-ISSN 3032-1972

Effect of corrosion rate and hardness of titanium in Kokubo's simulated body fluid for orthodontic applications

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Abstract. Titanium and its alloys are widely recognized as preferred materials for dental implants, particularly in orthodontic applications, owing to their superior corrosion resistance and mechanical performance compared with stainless steel. However, certain limitations remain. In acidic environments, titanium's corrosion resistance tends to decline. This issue is of particular relevance in West Sumatra, where local dietary habits include frequent consumption of acidic and high-fat foods such as rendang, gulai and various fried dishes. Hence, it is important to evaluate the corrosion behavior of titanium and its alloys under acidic conditions. In this study, four titanium-based materials were investigated: Ti-12 Cr, TNTZ-ST, Ti-64 ELI (Extra Low Interstitial), and Commercially Pure Titanium (CpTi). Immersion tests were performed in Kokubo's Simulated Body Fluid (SBF) at pH 5.0 for four exposure periods (1, 2, 3, and 4 weeks). The corrosion rate was determined using the weight loss method. Results revealed that CpTi exhibited the highest corrosion rate (0.0985 mm/y) after 4 weeks, while Ti-12 Cr demonstrated the lowest (0.0515 mm/y). Regarding hardness, CpTi reached the highest value (365 HVN at 1 week), whereas Ti-12 Cr recorded the lowest (130 HVN).

Keywords: biocompatibility, corrosion, Kokubo SBF, titanium, weight loss method

Received: 30 September 2025; **Presented:** **9** October 2025; **Publication:** 9 March 2026
DOI: https://doi.org/10.71452/38n0c342

INTRODUCTION

Orthodontic wire materials must be biocompatible to prevent adverse biological responses. In addition, high corrosion resistance is essential to ensure durability and safety in the oral environment [1]. Stainless steel has long been used as an orthodontic material due to its affordability, availability, and favorable mechanical properties, including high hardness and tensile strength (500 MPa), as well as acceptable levels of corrosion resistance and biocompatibility.

Nevertheless, stainless steel presents several limitations. Its stiffness is relatively high, with an elastic modulus of approximately 200 GPa, which may pose clinical drawbacks. Furthermore, the presence of nickel (Ni) in stainless steel alloys may cause toxic effects and allergic reactions, including itching, oral ulcers, and gum inflammation [2]. These limitations have led to increasing interest in pure titanium and titanium alloys as alternative orthodontic materials.

Titanium exhibits superior biocompatibility and biomechanical properties compared with other metals, including stainless steel. It is free from nickel, making it safer for intraoral use. Both Commercially Pure Titanium (CpTi) and Ti-64 Extra Low Interstitial (ELI) have been approved by the American Society for Testing and Materials (ASTM) as standard biomaterials [1,2].

Despite their excellent corrosion resistance, titanium and its alloys may experience reduced performance in acidic conditions [3]. This is particularly relevant in regions such as West Sumatra, where traditional foods are rich in acidic compounds and coconut milk. Previous studies have shown that fluoride and chloride ions at concentrations exceeding 0.5% accelerate the degradation of the titanium oxide layer [3,4]. Such degradation is associated with increased corrosion activity, especially in acidic saliva environments.

For example, pure titanium immersed in artificial saliva at pH 6.0 demonstrated a corrosion rate of 0.00000030 mm/y after 168 hours. Similarly, stainless steel exposed to carbonated beverages at the same pH showed a corrosion rate of 0.00000055 mm/y. Titanium immersed in Artificial Blood Plasma (ABP) at pH 6.0 for four weeks exhibited a corrosion rate of 0.00000072 mm/y [5–9]. These findings suggest that decreasing pH (<7) weakens the protective titanium oxide layer, thereby accelerating corrosion.

Based on the existing literature, most corrosion studies have focused only on pure titanium and stainless steel. Research on other titanium alloys remains limited. Therefore, the present study investigates Ti-64 ELI, TNTZ (Titanium-Niobium-Tantalum-Zirconium), and Ti-12 Cr, in addition to CpTi. The aim is to compare their corrosion rates and hardness to identify which alloy offers superior performance in acidic environments. This research aligns with the 2025–2029 research roadmap of the Mechanical Engineering Department, Universitas Dharma Andalas, which emphasizes the development of innovative concepts in materials engineering, particularly biomaterials.

e-ISSN 2623-0313
p-ISSN 3032-1972

METHODOLOGY

This study employed an experimental approach that combined qualitative and quantitative methods. Immersion tests were conducted over four exposure periods (1, 2, 3, and 4 weeks) in accordance with ASTM G31-72 [11]. Four types of titanium samples—Ti-12 Cr, TNTZ-ST, Ti-64 ELI, and CpTi—were prepared, with the specimen design illustrated in Figure 1.

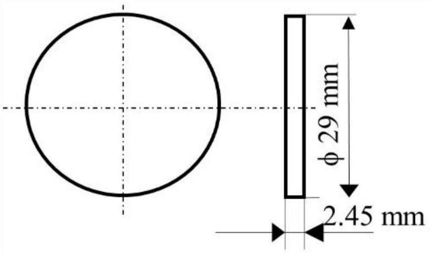

Figure 1. The test specimen followed the ASTM G31-72 standard

The specimens were immersed vertically in Kokubo's Simulated Body Fluid (SBF) solution (pH 5.0), as shown in Figure 2, ensuring full surface exposure. The tests were conducted at room temperature (27 °C) under open-air conditions.

Figure 2. Beaker (50 ml) containing test specimens.

The artificial saliva composition was modified to achieve a pH of 5.0 by adjusting the KCl concentration. Initially, 0.225 g/L of KCl was added, but 0.57 g/L was ultimately required to obtain the desired acidity. The pH was verified using both litmus paper and a digital pH tester, yielding a consistent value of 5.0. The artificial saliva was prepared at the Pharmacy Laboratory, Universitas Dharma Andalas. Table 1 presents the chemical composition of Kokubo's SBF used in this study [9,10].

Table 1. Composition of Kokubo's Simulated Body Fluid.

No	Chemical compound	Qty
1	NaCl	8.035 gr
2	$NaHCO_3$	0.355 gr
3	KCl	0.225 gr
4	K_2HPO_4 $3H_2O$	0.231 gr
5	MgCl $6H_2O$	0.311 gr
6	1.0M-HCl	39 ml
7	$CaCl_2$	0.292 gr
8	Na_2SO_4	0.072 gr
9	Tris	6.118 gr
10	1.0M-HCl	0-5 ml

To determine weight loss, a digital analytical balance (KERN ABJ) was used. This balance was used to measure the initial and final weights of the specimens, with a precision of up to 5 decimal places. The corrosion rate values were then calculated accordingly [2,3]. Meanwhile, hardness values were obtained using the Vickers Hardness (VHN) method, in accordance with ASTM Standard Test Methods for Knoop and Vickers Hardness of Materials [11]. The indenter used in this test was a square-based pyramid with an angle of 136°, and the indentation time was maintained at 10-15 seconds.

DISCUSSION AND ANALYSIS

1. Corrosion Rate

The results indicate that all specimens exhibited an increase in corrosion rate with longer immersion time. The highest corrosion rate was observed in CpTi (0.0985 mm/y) after 4 weeks of exposure, while the lowest was observed in Ti-12Cr (0.0515 mm/y). This finding suggests that the addition of alloying elements, such as chromium (Cr), enhances the corrosion resistance of titanium in acidic environments by promoting the formation of a more stable passive layer.

Immersion tests using the weight-loss method showed that the decrease in specimen weight was directly proportional to the exposure duration (t). The weight reduction was attributed to uniform corrosion occurring on the specimen surface. At 1 week of immersion, the weight loss was not significant, likely due to the relatively short exposure time, during which only inclusions or surface impurities adhered to the specimen [12]. Noticeable weight loss began to occur after 2, 3, and 4 weeks of immersion. The weight-loss results for the specimens are presented in Table 2.

e-ISSN 2623-0313
p-ISSN 3032-1972

Table 2. Weight loss results of test specimens after immersion test

No	Material	*Weight loss* (gr)			
		Week1st	Week2nd	Week3rd	Week4th
1	CPTi	0,0578	0,0624	0,0715	0,987
2	Ti-64 ELI	0,0457	0,0583	0,0664	0,726
3	TNTZ-ST	0,0356	0,4392	0,0593	0,594
4	Ti-12 Cr	0,0255	0,0451	0,0552	0,513

The corrosion rate values were also directly proportional to the reduction in specimen weight with increasing testing time (t), as shown in Table 3 and Figure 3. The experimental results indicate that the corrosion rate of titanium alloys was lower compared to that of commercially pure titanium (CpTi). Titanium alloys exhibited a longer corrosion lifetime than CpTi. This improvement can be attributed to the presence of alloying elements that provide solid solution strengthening, such as aluminum (Al), copper (Cu), chromium (Cr), and zirconium (Zr), which enhance the corrosion resistance of titanium alloys relative to CpTi.

Table 3. Corrosion rate of specimens determined using the weight loss method

No	Material	Corrosion Rate (mm/y)			
		Week1st	Week2nd	Week3rd	Week4th
1	CPTi	0,0475	0,0525	0,0615	0,0985
2	Ti-64 ELI	0,0358	0,0487	0,0568	0,0725
3	TNTZ-ST	0,0254	0,0397	0,0498	0,0595
4	Ti-12 Cr	0,0155	0,0355	0,0458	0,0515

Among the titanium alloys, Ti-12Cr exhibited the lowest corrosion rate, followed by TNTZ and Ti-64 ELI. This is attributed to the presence of chromium (Cr), which forms a stable passive layer on the Ti-12Cr surface. In addition, the Ti-12Cr specimens in this study demonstrated higher strength after aging at 30 Ks.

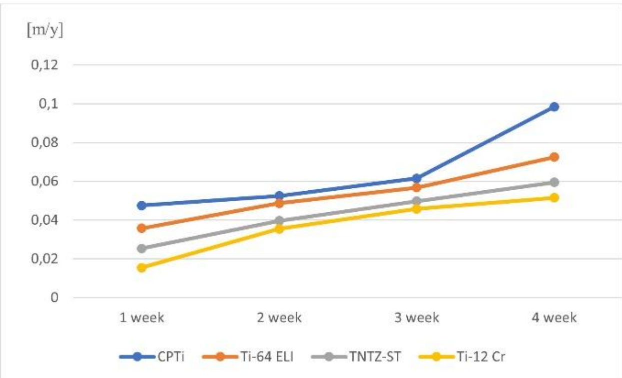

Figure 3. Corrosion rate of titanium as a function of immersion time.

2. Hardness Value

The hardness values decreased in all materials with increasing immersion time. CpTi exhibited the highest hardness, indicating superior mechanical properties; however, its corrosion resistance was lower compared to Cr-containing alloys [13]. These findings suggest that for dental implant applications in communities with high consumption of acidic foods and coconut milk, titanium alloys containing chromium (such as Ti-12Cr) are more suitable than commercially pure titanium. Detailed results are presented in Table 4 and Figure 4.

Table 4. Hardness values of titanium after the immersion test

No	Material	Hardness Value (HVN)			
		Week1st	Week2nd	Week3rd	Week4th
1	CPTi	365	346	328	310
2	Ti-64 ELI	310	305	290	280
3	TNTZ-ST	286	254	236	216
4	Ti-12 Cr	165	156	145	130

The hardness values obtained in this study exhibited an inverse correlation with both immersion time (t) and corrosion rate. As shown in Figure 4, hardness progressively decreased with increasing immersion

e-ISSN 2623-0313
p-ISSN 3032-1972

duration. This reduction in hardness was associated with increasing corrosion rates, particularly when corrosion led to pronounced surface degradation. The underlying mechanism is the gradual erosion of the metallic surface in acidic or chloride-containing environments, which compromises the protective titanium oxide passive film. The disruption of this oxide layer renders the surface more vulnerable to subsequent attack, thereby weakening the near-surface microstructure. Furthermore, the decrease in hardness may also result from microstructural alterations within the titanium itself. Diffusion of ions from the corrosive environment into the surface can promote the formation of secondary phases or precipitates, which, in turn, diminishes the local mechanical strength.

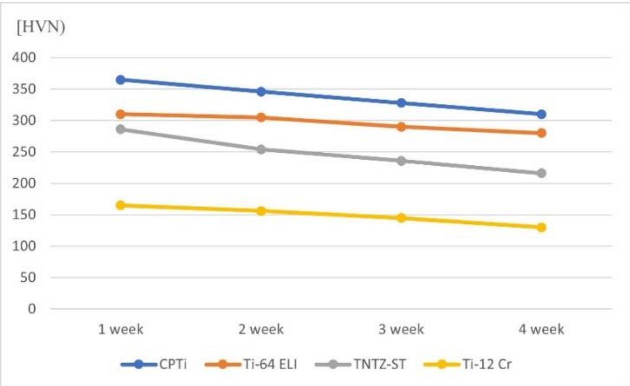

Figure 4. Variation of titanium hardness with immersion time

CONCLUSION

From the results of this study, it can be concluded that the highest corrosion rate occurred in CpTi (0.0985 mm/y) after four weeks of immersion, while the lowest was observed in Ti-12Cr (0.0515 mm/y). In terms of hardness, CpTi exhibited the highest value (310 HVN) at the fourth week, whereas Ti-12Cr showed the lowest (130 HVN) over the same period. The incorporation of chromium into titanium alloys significantly improved corrosion resistance in acidic environments. Therefore, for orthodontic applications exposed to acidic conditions, Ti-12Cr is recommended owing to its superior corrosion resistance.

ACKNOWLEDGMENT

The authors gratefully acknowledge Dharma Andalas University for providing research funding support through the Doctoral Research Grant during the 2024/2025 academic year.

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