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Evaluation of Ti-Cr-Cu Alloys for Dental Applications

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This study examined the characteristics of as-cast Ti-Cr(7-19%)-Cu(3-7%) (all percentages in this article are mass%) alloys to evaluate their suitability for dental applications; studies on the alloy structures and mechanical properties, grindability, and corrosion behavior were included in the investigation. The alloys were centrifugally cast and bench-cooled in investment molds. The x-ray diffractometry of the as-cast alloys bench-cooled in the molds indicated the following phases: α+β+ω in the 7% Cr and 7%Cr+3%Cu; β+ω in the 13%Cr; and β in the 13%Cr+3%Cu through the 19%Cr+3%Cu alloys. The strengths of the binary β Ti-Cr and ternary β Ti-Cr-Cu alloys with 13 and 19% Cr were approximately two times higher than those of CP Ti. The alloy ductility was dependent on the chemical composition and thus, the microstructure. The 7% Cr alloys were extremely brittle and hard due to the ω phase, but the ductility was restored in the 13 and 19% Cr alloys. The hardness (HV) of the cast 13 and 19% Cr alloys was approximately 300-350 compared with a value of 200 for CP Ti. The grindability of the cast alloys was examined using a rotating SiC wheel at speeds (circumferential) of 500 and 1250 m/min. At the higher speed, the grindability of the 13 and 19% Cr alloys increased with the Cu content. The grindability of the 13% Cr alloy with 7% Cu was similar to that of CP Ti. Evaluation of the corrosion behavior in an artificial saliva revealed that the alloys are like many other titanium alloys within the normal intraoral oxidation potential. The wear resistance testing of these alloys also showed favorable results.

Keywords corrosion resistance, grindability, titanium alloys, wear resistance

1. Introduction

Titanium (Ti) has established a firm position as a biomedical material over the last 20 years. The reasons for this widespread acceptance are rooted in its outstanding corrosion resistance and biocompatibility, together with appropriate mechanical properties. However, when higher strength than that provided by commercially pure titanium (CP Ti) is needed, one solution is to use an as-cast alloy. This alternative is used in dentistry because the as-cast metals are not subjected to any additional metallurgical processes. Because β Ti is the most versatile kind of Ti alloy, a large number of studies have been performed on various aspects of its metallurgy (Ref 1). The β phase is retained in metastable form by quenching the alloy with a sufficient amount of β stabilizing elements to depress the martensite finish temperature to below room temperature (Ref 2). If most of the β phase is retained, the alloy has good ductility. However, at certain alloy compositions, the β phase partially decomposes during rapid cooling into an intermediate phase known as the omega (ω) phase; it has been known for a long time that this phase reduces the ductility (Ref 3). Many investigators have studied alloy systems to characterize the effect of alloying elements on the phases formed and to identify the ω phase, the kinetics of transformation in such systems, and their crystal structures (Ref 4).

This study examined the effect of using chromium (Cr) as an alloying element for several reasons. One drawback of alloying pure Ti is that its superior corrosion resistance may be jeopardized. Chromium is known to control the anodic activity of the alloy and increase the tendency of Ti to passivate (Ref 5). In fact, it has already been used for many years as a major constituent in dental casting alloys (Ref 6). An additional advantage of alloying Cr to Ti is that the liquidus temperature is gradually reduced from the high melting point of pure Ti (1670 °C) until reaching a minimum of 1410 °C at a Cr content of 46% Cr (Ref 7). Also, the β phase can be retained in the as-cast structure, depending on the amount of Cr and the cooling speed (Ref 8). The former facilitates the casting procedure with less contamination, and the latter forms metal with better ductility resulting from the β BCC structure, which is beneficial when dental appliances require some ductility.

Besides adequate strength, other requirements for dental alloys include good grindability or machinability and acceptable wear resistance, properties in which pure titanium is known to be poor (Ref 9). We studied the effect of copper (Cu) on these properties and found marked improvement due to the introduction of a Ti_2Cu eutectoid constituent or some type of precipitation and/or a multiphase structure (Ref 10). Another merit of Cu is the reduction of the liquidus temperature of the Ti-Cu alloy system (Ref 7).

Although Cr is one of the alloying elements in various multicomponent commercial alloys, reports on the mechanical properties of binary Ti-Cr alloys are limited. Two independent investigations performed at dental schools (Ref 11, 12) reported on the feasibility of casting binary Ti-Cr alloys. A

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search of the literature did not turn up anything on ternary Ti-Cr-Cu alloys.

In view of several beneficial effects of alloying Cr and Cu with titanium, we characterized a series of experimental binary Ti-Cr alloys and ternary Ti-Cr-Cu alloys in an effort to find an optimal alloy composition for a dental casting alloy. This article summarizes the test results of the alloy structures, mechanical properties, grindability, and corrosion characteristics of these alloys. The results of wear testing are also discussed.

2. Selection of Alloys

The critical minimum level of stabilizing β phase (β_c) for Cr is reported to be 6.5% (Ref 1). Alloys with three concentrations of Cr (7, 13, and 19 mass%; hereafter "mass%" will be referred to as "%"), which covered the β_c of Cr, were prepared to determine whether the β phase could be retained in the as-cast specimens that were bench-cooled in investment molds. Because binary Ti-Cr alloys form a eutectoid system at a composition of about 13.4% Cr (Ref 7), the three experimental binary alloys should represent the hypoeutectoid, the near eutectoid, and the hypereutectoid alloys at equilibrium. On the other hand, in our previous studies on the grindability (Ref 13) and wear behavior (Ref 10) of binary Ti-Cu alloys, it was found that these properties greatly improved at the 5% Cu alloy composition. Using this amount as a benchmark, three Cu concentrations (3%, 5%, and 7% Cu) were selected. A total of three binary Ti-Cr alloys [Ti-7%Cr (7Cr); Ti-13%Cr (13Cr); and Ti-19%Cr (19Cr)] and five ternary Ti-Cr-Cu alloys [Ti-7%Cr-3%Cu (7Cr3Cu); Ti-13%Cr-3%Cu (13Cr3Cu); Ti-13%Cr-5%Cu (13Cr5Cu), Ti-13%Cr-7%Cu (13Cr7Cu); and Ti-19%Cr-3%Cu (19Cr3Cu)] were investigated.

2.1 Alloy Fabrication

Titanium sponge (>99.8%, grade S-90, Sumitomo Titanium Corp., Amagasaki, Japan), pure electrolytic Cr (>99.9% metal base, Nichijya New Materials, Tokyo, Japan), and an oxygen-free high-purity copper (99.99%, The Research Institute for Electric and Magnetic Materials, Sendai, Japan) were used to prepare the alloys. A total of 30 g of the desired amounts of these metals was melted together on a water-cooled Cu hearth in an argon-arc melting furnace (TAM-45, Tachibana Riko, Sendai, Japan) using high-purity argon (99.9999%, Nippon Sanso, Kawasaki, Japan). Each metal was melted six times by inverting it after every melt to ensure homogeneity of the alloy constituents.

3. Casting Patterns

Four patterns were invested to make the castings: (a) dumbbell-shaped plastic patterns for mechanical property testing (20 mm gauge length, 2.8 mm diam.); (b) wax plate patterns for corrosion testing and x-ray diffractometry (10 × 10 × 2 mm); (c) two sizes of patterns for grindability testing (3 × 8 × 30 mm; 3.5 × 8.5 × 30.5 mm) so that the larger castings were the same size as the smaller ones after removal of the α case; and (d) disc wax patterns (5 mm long, 4 mm diam.) for metallography and microhardness testing.

3.1 Casting Procedures

Each alloy was placed in a dental casting machine (Ticast Super R, Selec, Osaka, Japan), and the melting/casting chamber was evacuated to 7×10^{-2} Pa (5×10^{-4} Torr). The alloy was then arc-melted at a pressure of 2.8×10^4 Pa (200 Torr) in a high-purity argon atmosphere (99.999%, Ultra High Purity Argon, Gasco, Dallas, TX) and centrifugally cast into a magnesia-based mold (Selevest CB, Selec) at 200 °C. The main constituents of the investment materials were MgO, CaO, and Al_2O_3, plus Zr powder. After the castings were made, they were bench-cooled without removing the mold from the castings. The internal porosity of the cast specimens was examined with a conventional dental x-ray unit (Dentsply Gendex BX900, Des Plaines, IL). CP Ti (ASTM Grade 2) specimens were cast as controls.

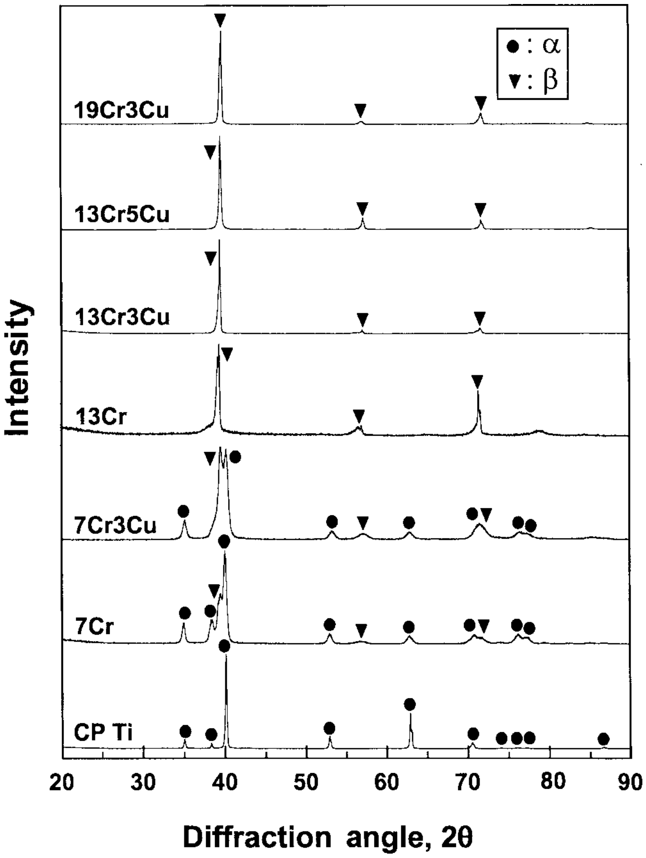

Fig. 1 XRD results at scan rate of 3.0°/min

4. X-Ray Diffraction

X-ray diffraction (XRD) (RINT 2000, Rigaku, Tokyo, Japan) was performed for the cast specimens of each metal using Cu Kα radiation generated at 50 kV and 300 mA and a scan rate of 3.0°/min. A minimum of two specimens per metal were ground down by approximately 250 μm to remove the α case before testing. The peaks of the XRD patterns were indexed to the ICDD (International Center for Diffraction Data) polycrystalline powder diffraction files (Ref 14). Figure 1 summarizes typical XRD patterns over 20-90° of the diffraction angles for all alloys and CP Ti. The diffraction patterns for the 13Cr7Cu and 19Cr specimens are not shown in the figure because they resemble those of 13Cr5Cu. α Ti (file #44-1294) peaks were found only for the CP Ti, 7Cr, and 7Cr3Cu patterns. β Ti (file #44-1288) peaks were found in the diffraction patterns of all the alloys. Because a minimal peak (not as prominent as the α Ti and β Ti peaks) was found near 80° in the 7Cr, 7Cr3Cu, and

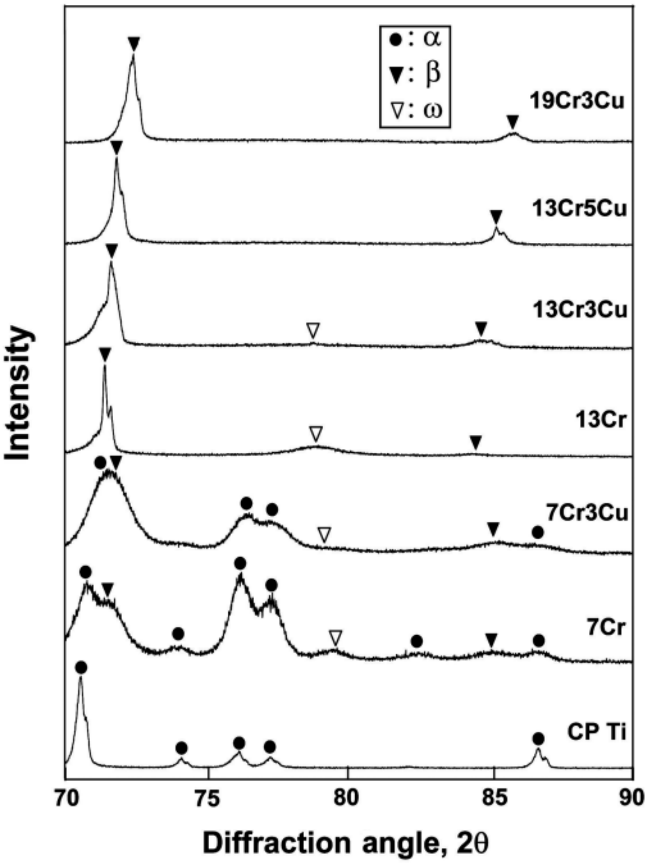

Fig. 2 XRD results at scan rate of 0.5°/min

13Cr patterns, XRD was done near this angle at a slower scan rate of 0.5°/min (Fig. 2). After reviewing Spachner's published *d*-spacings of the ω phase found in the quenched Ti-Cr (8%) alloy (Ref 4), this minimal broadened peak was identified as the likely ω phase of 2θ at 79.55 or 79.75° (arrows in Fig. 2). Also, a tiny ω peak was found in the 13Cr3Cu pattern although the peak was much less noticeable than in the other alloys. Apparently, more than 13% Cr is needed to fully retain the β phase in the Ti-Cr alloys. However, note that the ω peak decreased for the 7 and 13% Cr alloys due to alloying Cu. The addition of Cu (a β-stabilizing element) has the added effect of increasing the β-phase retention. Recently, Lin et al. (Ref 15) found that Cr had a similar effect as a β stabilizer in their bench-cooled specimens as Cu in our study. Their cast 7.5% Mo Ti alloy could fully retain the β phase through the addition of Cr; 7.5% Mo by itself was not enough to fully stabilize the β phase. It is common knowledge that the α′ or α″ phase forms in quenched β Ti alloys, including the Ti-Cr alloys (Ref 16-18). As described below, the microstructure of the 7% Cr specimens (Fig. 3) seemed to be an α′ martensite structure similar to that reported by Ericksen et al. (Ref 16) for the 5.1% Cr alloy. Lin et al. (Ref 15) identified the α″ phase in their 7.5% Mo alloy and 7.5% Mo + 1% Cu alloy. In our study (Fig. 2), the intensity of two α peaks (probably α′) of 2θ at 76.2° (112) and 77.4° (201) decreased notably in the 7Cr3Cu pattern compared with that of the 7Cr and completely disappeared in the 13Cr diffraction pattern. Further study is needed of the α phase in the 7% Cr alloys as to which form of the α phase it is. Our results indicate that alloying 13% Cr is sufficient to retain most of the β phase even with our cooling rate. It should also be noted that no peaks corresponding to intermetallic compounds ($TiCr_2$ and Ti_2Cu) that may have formed from the eutectoid reaction were detected in any of our specimens. The lack of such compounds was thought to be due to the detection limitations of the XRD system.

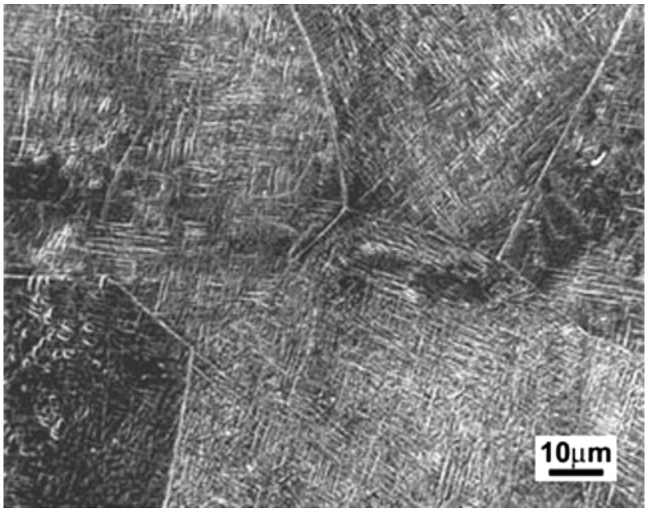

Fig. 3 Microstructure of as-cast 7Cr specimen

5. Microstructures

As-cast specimens of each metal (a minimum of two pieces) were examined using an optical microscope (Epiphot 200, Nikon, Japan) and a scanning electron microscope (SEM) (JSM-6300, JEOL, Japan) equipped with an energy dispersive spectrometer (EDS) analysis system using a Si (Li) x-ray detector (Noran Instruments, Middleton, WI). Figure 3 is a typical micrograph of an as-cast 7% Cr specimen. The fine acicular 7Cr microstructure is similar to that of the water-quenched 5.1% Cr alloy with α′ martensite reported by Erickson et al. (Ref 16). Their transmission electron microscopy (TEM) study revealed the existence of the ω phase in untransformed β-phase grains, which is consistent with our XRD data. In contrast to the 7% Cr alloy, the microstructures of the other alloys appeared to consist of equiaxed β-phase grains. A micrograph of an as-cast 13Cr3Cu specimen is shown in Fig. 4. A number of precipitates are evident inside the β grains. Judging from their morphology, they are likely the equilibrium, diffusionally transformed α phase formed from the β phase or ω phase during cooling. Williams (Ref 2) reported a similar precipitate in Ti-18%Mo alloys. The authors' x-ray diffractometry failed to detect the α phase in these alloys, probably due to an insufficient volume fraction of this phase.

6. Mechanical Properties

Tensile testing was performed using a universal testing machine (Model No. 1125, Instron Corp., Canton, MA) at room temperature at a crosshead speed of 0.25 mm/min. Three or four as-cast specimens of each metal were tested. The yield strength at 0.2% offset, ultimate tensile strength, and elongation determined for all metals are plotted in Fig. 5, which includes the phases identified.

The yield strengths and tensile strengths of all the 13Cr and 19Cr alloy series were all within the same range (855-967 MPa for yield strength; 906-989 MPa for tensile strength). These strengths were more than double those of CP Ti. Although

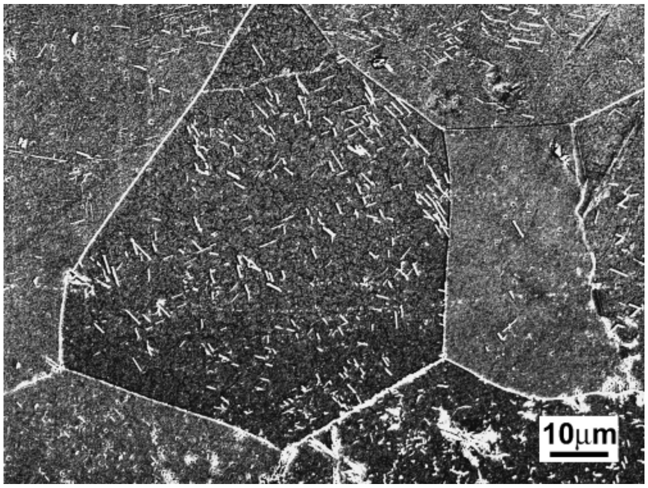

Fig. 4 Microstructure of as-cast 13Cr3Cu specimen

significant differences were found among some alloys, the differences in their strength were too minimal to mention. In contrast, the elongation of the alloys was dependent on the alloy microstructure and thus, on the chemical composition. The elongation of 7Cr and 7Cr3Cu is plotted as zero (Fig. 5), because both ends of the tensile specimens were too brittle to grip during testing. These tensile test results can be explained with the aid of the above XRD and metallographic findings. The extreme brittleness of the 7Cr alloys was attributed to the presence of the ω phase in the α martensite: increasing the Cr concentration to 13% began stabilizing more β phase, but good ductility was not obtained with the minimal amount of ω phase present. However, alloying 3% Cu helped to retain the β phase completely, resulting in increased ductility. The ductility of the 13% and 19% Cr alloys decreased with the addition of Cu. This decrease is believed to be the result of the inclusion of the eutectoid constituents, $TiCr_2$ and/or Ti_2Cu, in the microstructures. However, the XRD and microstructural examination failed to find these constituents, probably due to the limited detection capability of the x-ray diffractometer. Increasing Cr to 19% produced the best ductility in the alloys tested, as the Cr content was considerably greater than the β_c value (6.5%) in the Ti-Cr alloys. As in other alloys, there was a reduction in the ductility due to the effect of Cu. The tensile test data for binary Ti-Cr alloys found earlier by Okuno et al. (Ref 11) were 764 MPa (10%Cr) and 970 MPa (20%Cr); the elongation values were 0.2% (10%Cr) and 2.8% (20% Cr).

The modulus of elasticity for all the tested metals is included in Fig. 5. As expected, the value of α CP Ti is higher than that of all the β alloys. The high value for 13Cr can be explained by the presence of the ω phase (Ref 19).

6.1 Hardness

Changes in the microhardness of the polished cross sections from the cast surface to a depth of 500 μm for all the metals studied are summarized in Fig. 6. The results indicated that the hardened α case formed on all the metals. The thickness of the α case in CP Ti was approximately 200 μm, while the α case in the alloys tested was approximately 100 μm thick. In a previous study, it was explained thermodynamically why the α case on the Ti alloys is thinner than on CP Ti (Ref 20). The hardness of the interior structures of CP Ti was (significantly) the lowest, and the two 7Cr and 7Cr3Cu alloys with the ω phase had the highest hardness values. Note that the interior hardness was the same as the surface hardness in these two alloys. The high hardness of the interior structure of these alloys resulted from the martensitic fine microstructure. All the other β alloys had a medium level of hardness with a slightly higher value for 13Cr, which also contained the ω phase.

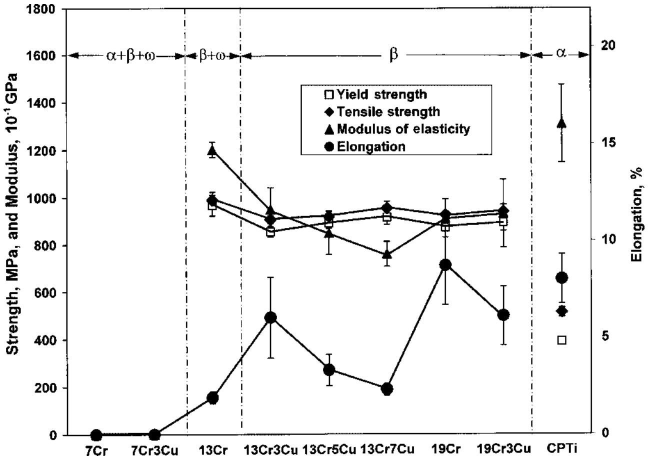

Fig. 5 Properties of metals tested

6.2 Grindability

As in the other grindability tests performed on several titanium alloys (Ref 13), the authors evaluated the ease of grinding of the present binary Ti-Cr and ternary Ti-Cr-Cu alloy series by grinding the metal specimens with a SiC wheel (1.5 mm thick, 13 mm diam.; 703-120, Brasseler, Savannah, GA). The grinding wheel was attached to a dental handpiece (Upower model 501, Brasseler USA) secured to the grinding apparatus. Two types of specimens were tested: those with as-cast surfaces with the α case intact, and those with the α case completely removed (250 μm was ground from all six as-cast surfaces of the rectangular specimens). In the grinding test, one of the side walls of the specimen (3.0 × 8.0 mm surface) was placed horizontally against the circumferential surface of the SiC wheel and ground with a force of 100 gf (0.98 N). The grindability was assessed by determining the volume of metal ground from the specimen during one continuous minute of grinding. The two rotational (circumferential) wheel speeds used were 500 or 1250 m/min.

Among the metals tested, four metals (7Cr, 7Cr3Cu, 13Cr7Cu, and CP Ti) exhibited the best grindability. From the results on grindability versus ductility for various α, α+β, and β Ti alloys (Ref 21), it was found that the grindability improved with a reduction in ductility when the plastic deformation was restricted by certain structures. Thus, the high grindability of 7Cr and 7Cr3Cu resulted from the brittle nature of the alloys containing the ω phase. The ductility of the 13Cr alloys was reduced by adding Cu, making 13Cr7Cu one of the alloys with the highest grindability. It was speculated that an increase of the eutectoid constituent with the increase in Cu in the microstructure, which reduced the ductility, enhanced the grinding process even for the ductile β Ti-Cr alloys. A similar tendency in the relationship of increasing grindability and the reduction in ductility was found for the 19Cr alloys. As stated above in the sections on XRD and microstructure, the existence of the eutectoids has not been verified. Another notable result is the high grindability of CP Ti, which may be attributed to the limited slip system of its close-packed hexagonal crystal structure. Figure 7 shows a summary of the grindability at 1250

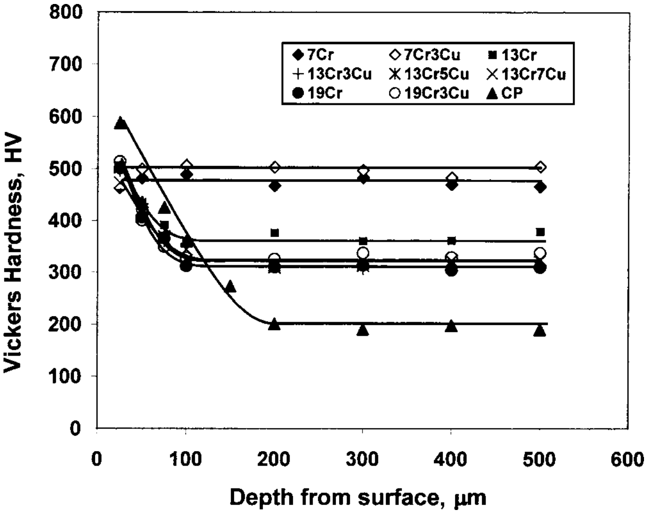

Fig. 6 Changes in microhardness of alloys tested

m/min for all the metals tested with the α case intact; the elongation corresponding to each metal is also included. The grindability in both the 13Cr and 19Cr series increased with an increasing amount of Cu, which is consistent with the authors' previous finding of a negative correlation for the ductility versus grindability. Increasing the Cu probably increased the amount of the eutectoid constituent, which apparently worked effectively at improving the grindability, even in ductile β Ti-Cr alloys. Also notable is that the grindability of 13Cr7Cu is similar to that of CP Ti. Although not shown in the figure, a similar trend was found for the specimens without α case ground at 1250 m/min. No eutectoid effect was found in specimens ground at the slower speed (500 m/min). The overall amounts ground were smaller at the lower speed than at the higher speed.

In a previous investigation evaluating the wear resistance of some titanium alloys (Ref 21), it was found that the microstructural modifications of titanium alloys that reduced the plastic deformation favored the wear resistance, in addition to the grindability. In the in vitro two-body wear test simulating intraoral chewing action, the eutectoid effect was found in the 13% Cr Ti alloys. The amount of wear significantly decreased with increasing concentrations (3, 5, and 7%) of Cu. The wear of 13Cr7Cu was less than one-third that of CP Ti or 13% Cr Ti (Ref 22). The trend for the grindability of specimens with and without the α case was that, at the lower grinding speed, the grindability was higher in each pair of alloys for specimens without the α case but at the higher grinding speed, grindability was higher with the α case in each pair of alloys. Further studies are needed to clarify the effect of the α case.

6.3 Corrosion Behavior

The corrosion behavior of all the metals tested was evaluated using slightly polished specimens (30 μm from the cast surface) and the electrolytic method and potentiostatic polarization technique, as previously performed for various titanium alloys (Ref 23). The corrosion evaluations were performed in modified Tani-Zucchi synthetic saliva (1.5 g KCl, 1.5 g $NaHCO_3$, 0.5 g $NaH_2PO_4 \cdot H_2O$, 0.5 KSCN, 0.9 g lactic acid dissolved in 1000 ml of H_2O) (Ref 23). The data obtained included polarization resistance (R_p, $M\Omega \cdot cm^2$), cathodic Tafel slope (β_c, V/decade), anodic Tafel slope (β_a, V/decade), corrosion current density [$I_{corr} = (\beta_a\beta_c)/[2.3R_p(\beta_a + \beta_c)]$], passive current density (I_{pass}, A/cm^2), and breakdown potential (E_b, V).

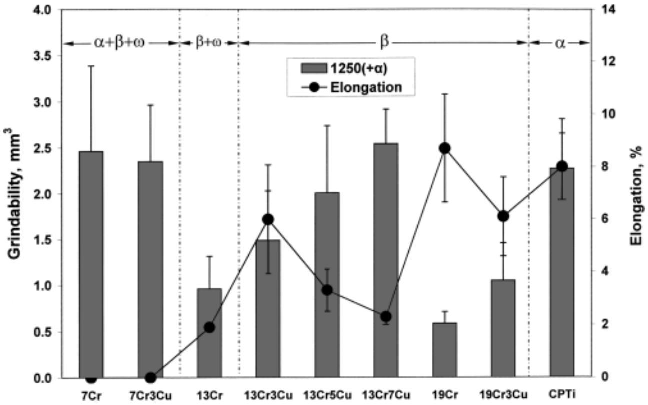

Fig. 7 Grindability of metals tested (1250 m/min)

The determination of the open circuit potential (OCP) of the present series of Ti-Cr and Ti-Cr-Cu alloys and CP Ti showed a quick initial potential increase, followed by a stabilizing potential, indicating the rapid formation of a protective film on the specimen surfaces. Table 1 summarizes the corrosion data for all the metals tested. There were statistical differences among the metals for the polarization resistance (R_p), corrosion current density (I_{corr}), and passive current density (I_{pass}). CP Ti had the highest R_p and the lowest I_{corr} and I_{pass} values among the metals examined, which indicated its excellent corrosion resistance compared with the other metals in this study. Although the R_p, I_{corr}, and I_{pass} values of the Ti-Cr and Ti-Cr-Cu alloy series scattered from metal to metal, there was no trend indicating that the addition of Cr and Cu to Ti deteriorated the corrosion behavior of these alloys in artificial saliva.

Typical anodic polarization diagrams of the 13% Cr Ti with Cu series are shown in Fig. 8. Passivation started at approximately 200 mV. The ranges of the passive region seemed to decrease when the alloys contained Cu. No abrupt electrochemical activities or reactions were observed. These alloys had excellent passivation and corrosion characteristics in the oxidation potential range in the normal human oral cavity [−58 mV to 212 mV versus saturated calomel electrode (SCE)] (Ref 24) (see shaded band in Fig. 8).

The excellent corrosion behavior of the present alloys under experimental conditions is not surprising because Ti and Cr correspond to a typical passive metal combination (Ref 25). Although the conditions under which an oxide film is formed for Cr and Ti are different, these two metals may have complemented each other in forming a passive oxide film on the alloy surfaces. Several investigators have reported oxide films on Ti alloys: the formation of a Ti/Cr oxyhydroxide on Ti-Cr (37-73 at.%) in HCl (Ref 25, 26); TiO_2 with trace amounts of Ni oxide and/or hydroxide on NiTi+Cr (0.19%) and NiTi+Cr (0.29%) and Cu (4.97) in a NaCl and lactic acid solution (Ref 27); and also Ti/Cr oxide with hydroxide on a 20% Cr Ti alloy in a NaCl solution with fluoride (Ref 28). In each case, all these oxides/hydroxides contributed to their excellent corrosion resistance. The authors reported that thermodynamically, Ti in a solid solution of a Ti alloy can be oxidized easily and can probably form Ti oxide passivation films similar to pure Ti (Ref 29).

7. Summary

The microstructures, mechanical properties, grindability, and corrosion behavior were examined for as-cast binary Ti-Cr (7-19%) and ternary Ti-Cr-Cu (3-7%) alloys. The 7% Cr alloys

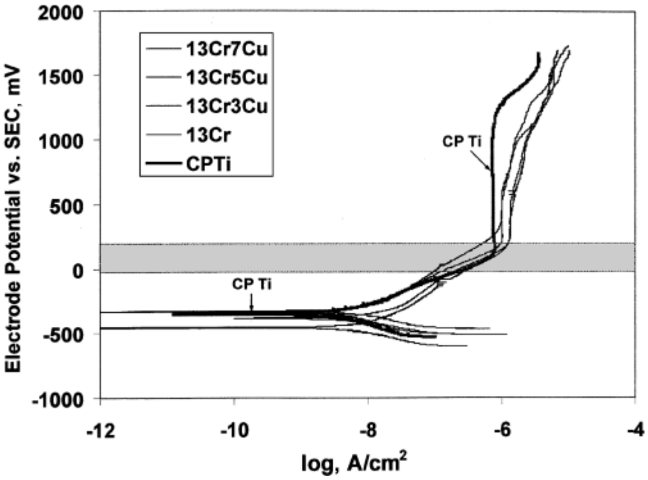

Fig. 8 Anodic polarization of 13% Ti Cr series

Table 1 Corrosion results for metals tested

Metals	OCP, mV	R_p, $M \cdot \Omega \cong cm^2$	I_{corr}, nA/cm^2	$I_{passive}$, nA/cm^2
CP Ti	−331 (45)(a)	3.11 (0.09)	12.7 (1.2)	755 (71)
7Cr	−307 (77)	2.41 (0.08)	17.5 (0.4)	826 (40)
7Cr3Cu	−271 (112)	1.21 (0.55)	63.7 (29.6)	1373 (110)
13Cr	−285 (126)	1.47 (0.65)	31.2 (11.7)	947 (132)
13Cr3Cu	−240 (89)	1.23 (0.59)	73.2 (76.8)	1302 (342)
13Cr5Cu	−247 (29)	2.08 (0.74)	25.4 (7.7)	943 (90)
13Cr7Cu	−231 (53)	2.20 (0.26)	17.6 (0.4)	926 (32)
19Cr	−215 (76)	1.71 (0.15)	22.6 (7.0)	998 (134)
19Cr3Cu	−206 (28)	1.43 (0.72)	42.8 (21.3)	1123 (313)

(a) Mean (one standard deviation)

were extremely brittle due to the ω phase in the structure. Elongation was restored with the 13% and 19% Cr alloys through the retention of the β phase. The elongation depended on the alloy composition: higher ductility was found in the 13Cr3Cu, 19Cr, and 19Cr3Cu alloys. Regardless of the higher hardness of these alloys, the grindability of some alloys was similar to that of CP Ti. There was no indication that the alloying elements at the concentration levels used in this study deteriorated the corrosion resistance of CP Ti, particularly within the normal intraoral potential. The wear resistance of the ternary alloys was determined to be outstanding. Cast Ti-Cr-Cu alloys can be used in dentistry when the properties of CP Ti are not sufficient for the particular application.

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