Unviersty of Anbar

Anbar Journal Of Engineering Science©

journal homepage: http://http://www.uoanbar.edu.iq/Evaluate/

Compression and Wear Properties of Biocompatible Commercially Pure Titanium and (Titanium-Silicon) Alloys

Emad S. Al-Hassani[a], Jamal J. Dawood[a], Balsam M. Al-Sabe'a [a]

[a] Materials Engineering Department, University of Technology, Iraq, 10.

PAPER INFO

Paper history:

Received ………

Received in revised form ………

Accepted ………

Keywords:

Porous Titanium, Biocompatible, Compression, Wear, (Ti-Si).

ABSTRACT

The porous Titanium is characterized by high permeability which can assure the ingrowth of bone tissues, and consequently results in a good bonding between the metallic implant and the bone. In this work, Silicon element was added to the Commercially Pure Titanium at different weight percent of (2, 4, 6, 8 and 10) to investigate its effect on the porosity percentage, mechanical properties of the resulted samples. XRD analysis stated that at (Si) content lower than (2 wt%) the alloy is single phase (α- Ti alloy), as the Silicon content increased, in addition to (α-phase), (Ti_5Si_3) intermetallic compound developed in the alloy. Porosity measurement results showed that the porosity percentage increases with the increase in Silicon content. Wear results stated that the wear rate increases with the increase in silicon content due to the increase in porosity percentage while the hardness results stated that there is no significant effect for Ti_5Si_3 intermetallic compound on improving the hardness of the samples. This is attributed to its low percent and the major effect of porosity on hardness which declined the effect of Ti_5Si_3 by reducing the hardness of the alloy compared with the master sample. The obtained results of the (yield strength, ultimate compressive strength and Young's modulus) were within the values that match bone's properties. This means these materials are suitable for biomedical application.

1. Introduction

One of the most hopeful engineering materials is Titanium, the interest in the application of Titanium alloys into tribological and mechanical components is rapidly growing in the field of biomedical, due to their attractive biocompatibility, mechanical properties, and high resistance to corrosion, Titanium and its alloys are used widely as implant materials; they have a wide range of biomedical applications including dental implants, surgical instruments and orthodontic applications **[1]**.

(Titanium-Silicon) alloys are new type of rapidly developing Titanium alloys. Their low processing cost, because of the lower melting point of Silicon as compared to pure Titanium, and their good formability make them a very promising alloy for casting. The (Titanium-Silicon) alloys strengthening mechanism is greatly different from the strengthening mechanism of traditional Titanium alloys. It consists of (Titanium matrix) as a continuous ductile phase and (Ti_5Si_3 reinforcing phase) as a second brittle phase **[2]**.

Meanwhile porous structures can improves osseointegration by facilitating cellular activities, such as the migration and proliferation of osteoblasts and mesenchymal cells as well as the transport of nutrients and oxygen required for vascularization during bone tissue development **[3]**. There are various methods to fabricate porous titanium scaffolds including powder metallurgy, foaming and additive manufacturing. With improved Osseo integration and similar properties to bone, instances of implant stress shielding and failure can be minimized. Many of the currently available porous metals do not meet the desired design criteria and have high manufacturing costs. However,

*Corresponding author.

E-mail address:…

the elastic modulus of titanium (110 GPa) is relatively higher than that of the human bone (4–30 GPa), leading to the stress-shielding phenomenon and subsequent implant loosening or bone resorption. To overcome this problem, it is possible to make the titanium with porous structure so that its elastic modulus can be reduced to be close to the elastic modulus of natural bone [3]. Porous structure of titanium not only reduces the stress-shielding, but it can also facilitate the bone ingrowth through the pores to strengthen the biological fixation of the implant **[4]**.

J.M. Oh et al., [5], examined the influence of adding trace (Silicon, Tin, Vanadium and Aluminum) on the mechanical and structural properties and grain refinement of pure Titanium. XRD results indicated that for alloys containing (Sn, V and Al) there was no shift of all the peaks observed by XRD even with increasing additives concentrations. Whereas for (Ti-Si) alloy all the peaks were slightly shifted to a higher angle with increased concentration of Silicon. Hardness test results stated that there was a gradual increase in the hardness of Titanium alloys containing (Al, V and Sn) additions with the increase in the alloying elements content. The hardness of (Ti-Si) alloy continuously increased with increasing Silicon content, thanks to the grain refinement effect.

Ivana Kopova et al., [6], evaluated the influence of adding silicon and iron on the (Ti–35Nb–7Zr–6Ta) alloy biocompatibility and mechanical properties. Adding small amounts of (0 - 1 wt% Silicon) and (0 - 2 wt% iron) to (Ti–35Nb–7Zr–6Ta) biocompatible alloy to increase its strength in condition of beta solution treatment. Additions of Silicon and iron results in noticeable rise in modulus of elasticity ranging from (65 - 85 GPa) and tensile strength from about (450MPa) to higher than (800MPa). However, the modulus of elasticity of (Ti–35Nb–7Zr–6Ta) alloy with added (silicon and iron) remains much smaller than the elastic modulus of (Ti64) alloy. Addition of Iron causes uniform elongation to increase due to increase in work hardening while the addition of silicon lowers the elongation to failure. (Ti–35Nb–7Zr–6Ta) with (0.5wt% Si+ 2wt% Fe) exhibits biocompatibility superior to that of (Ti64) alloy. (Ti–35Nb–7Zr–6Ta–2Fe–0.5Si) alloy exhibits best combination of biological and mechanical properties, this made it good candidate for bone implants used in load bearing.

Yunhui Chen et al., [3], evaluated the biocompatibility of scaffolds fabricated of porous Titanium and their mechanical properties used in engineering of bone tissue. Titanium porous scaffold was produced by powder metallurgy with using Magnesium powder as a space holder material which was pressed with Titanium powder and removed during firing. Assessment of the mechanical properties and porosity exhibited high compatibility level with cortical bone of human. The Young's modulus decreases with porosity as (44.2 GPa at 30%), (24.7 GPa at 40%) and (15.4 GPa at 50%). Samples porosity well matches the porosity of natural bone (4-30 GPa). The yield strength was found to be (221.7 MPa at 30% porosity) and (117 MPa at 40%) these values of yield strengths are superior to human cortical bone (130-180 MPa).

In this work, the phase identification of (CP-Ti) and (Ti–Si) alloys in which the contents of Silicon are (2, 4, 6, 8 and 10 wt%) have been investigated by XRD analysis, together with the mechanical tests (hardness test, compression test and wear test) and the porosity measurement which carried out by Archimedes method.

2. Materials and Methods

In this work, Commercially Pure Titanium (CP-Ti) powder of (98.5% purity and 0.785μm particle size) and Silicon powder of (99.0% purity and 250 μm particle size) were used to prepare (CP-Ti) and a series of (Ti-Si) alloys of (0, 2, 4, 6, 8 and 10 wt% Si) samples of (13mm diameter), using Powder Metallurgy technique. The starting powders were weighed (8 gm) for each sample then blended and homogenized for (20 min.) in a ball mill type (CAPCO-9VS). After Blending, the powders were cold pressed at (3 tons for 2 min.) using hydraulic Press type (MEGA-KPD-50E), the sintering process of the compacted samples was carried out under high-purity argon atmosphere at (900°C and 10°C/sec heating rate for 2 hrs.) to improve bonding among the green sample particles.

To find out the composition and phase identification of each implant sample the (XRD) test was conducted by using Shimadzu (X-ray) diffractometer of type (xrd- 6000/7000) operated at (40 kV and 30 mA) with (Cu K α 1) radiation.

The porosity measurements of the sintered samples was determined by the Archimedes method (RADWAG PS 360/C/1), shown in **figure (1)**.

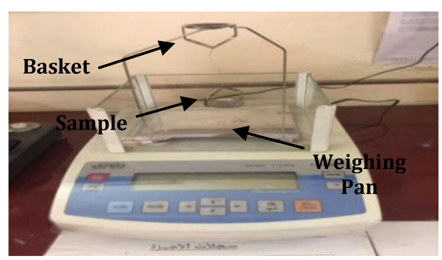


Figure 1. Porosity measurement device.

Vickers hardness analysis was performed using Vickers hardness tester of type (LARYEE Model HBRVS - 187.5), under a load of (30 Kg) with a maintaining time of (30 sec.) five indentations were taken.

Wear test was carried out for all samples under similar conditions of different loads of (5, 10 and15N) for a constant time interval of (5 minutes) using Pin-on-Disc testing method, as shown in **figure (2 a) and (2 b)**, which is used for tribological characterization.

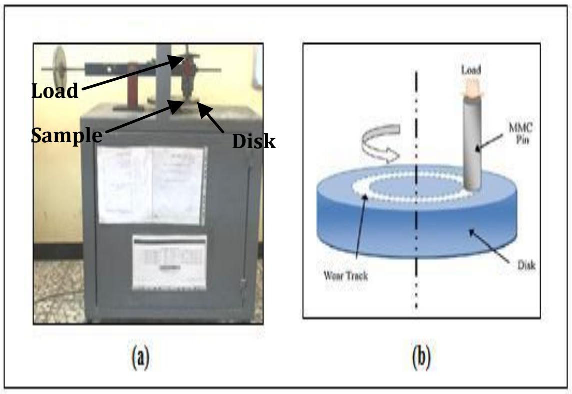


Figure 2. (a) Wear apparatus, (b) schematic views of the pin-on-disk apparatus.

The room temperature compression test was conducted on a universal mechanical test machine, of the type (LARYEE) with a load capacity of (50 KN). Cylindrical samples with height/diameter ratio of (2:1) were used and the compression test was performed at a crosshead speed of (2 mm/min) and the compressive load was applied gradually until the occurrence of fracture.

3. Results and Discussion

3.1. X-Ray Diffraction (XRD) and Microstructure Analysis

X-ray diffraction analysis of CP-Ti sample revealed only the peaks of the (α-phase), as shown in **figure (3 a)**, the addition of Silicon at (2 wt%) doesn't lead to the formation of a new phase or an intermetallic compound but resulted in changing the location and intensity of the (α-phase), as shown in **figure (3 b)**, due to the low Silicon content.

As the Silicon content reaches (4%) an intermetallic compound is formed as shown in **figure (3 c)** that represents the (XRD) pattern of (96%Ti-4%Si) sample, (α-phase) was obtained along with silicide precipitation, (Ti_5Si_3) intermetallic compound. For samples with (6, 8 and 10% wt) Silicon, the increase in silicon content only resulted in changing the location and intensity of the (α-phase) and the (Ti_5Si_3) intermetallic compound with no other new phases or intermetallic compounds. From the microstructure images, shown in the appendix, it is obvious that the use of powders with large differences in their particle size causes formation of highly porous alloys. The addition of Silicon element led to the production of single phase alloys with a high chance of producing intermetallic compound which changes the physical and chemical properties of the alloys according to the Silicon content.

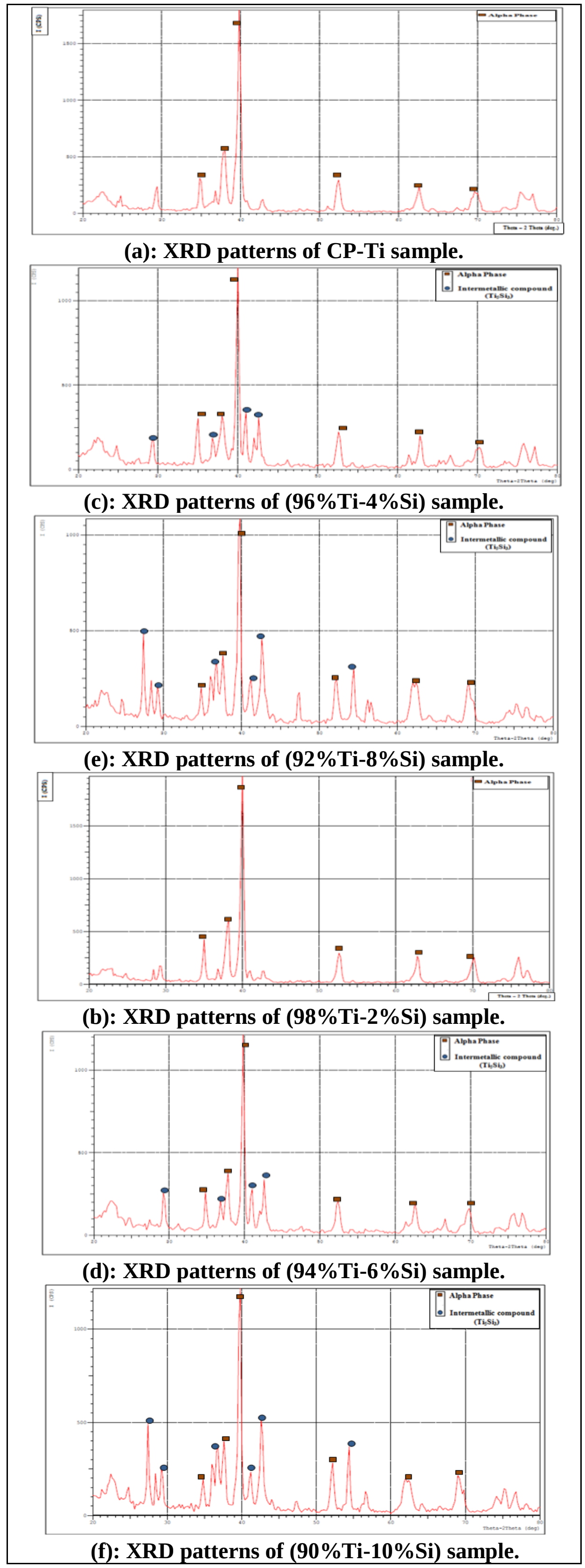


Figure 3. XRD patterns of the (CP-Ti) and (Ti–Si) alloys samples**.**

3.2 Porosity Measurements

The porosity percentages results of (CP-Ti) and (Ti-Si) alloys are graphically represented in **figure (4).** The graph shows an increasing in porosity percentage with the increase in Silicon content, as a result of using different powders (Ti, Si) with a large difference in their particle size, the particle size of Titanium powder was (0.785) µm while the particle size of Silicon was (250) µm.
The minimum value of porosity percentage was obtained in (CP-Ti) sample (without Si content) (12.4%) while the maximum value was obtained in the (Ti-Si) sample of (10% Si content), (30%).

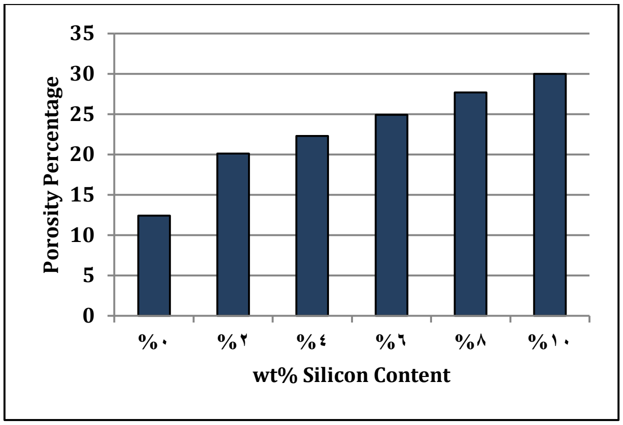


Figure 4. Porosity percentages.

3.3 Vickers Hardness

The sample (CP-Ti) presents the highest value for hardness of (199 HV) while the lowest hardness value of (52.6) was presented by the sample (90%Ti-10%Si), as shown in **figure (5)**. In conclusion, pores degrade the mechanical properties due to the reduced area supporting the load so the hardness decreases with the increase in porosity percentage from (12.4% for CP-Ti to 30% for 90%Ti-10%Si). Moreover there is no significant effect for Ti_5Si_3 intermetallic compound on improving the hardness of the samples and this is attributed to the Ti_5Si_3 low percent and the major effect of porosity on hardness which declined its effect.

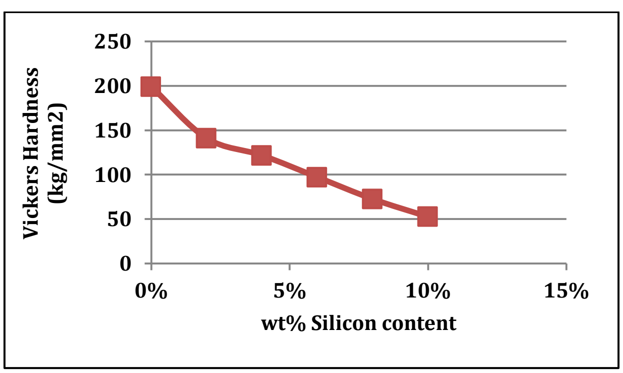


Figure 5. Vickers hardness.

3.4 Wear Rate

As the wear mechanism depends on the sample hardness which is a key parameter in governing the amount of material removal and as the wear rate is based on the weight loss through the process of material removal via the sliding of abrasives on the solid sample surface, the highest wear rate is presented by the sample (CP-Ti) with the highest hardness of (199 HV) while the lowest wear rate was presented by the sample (90%Ti-10%Si) with the lowest hardness of (52.6 HV), as shown in **figure (6)**.

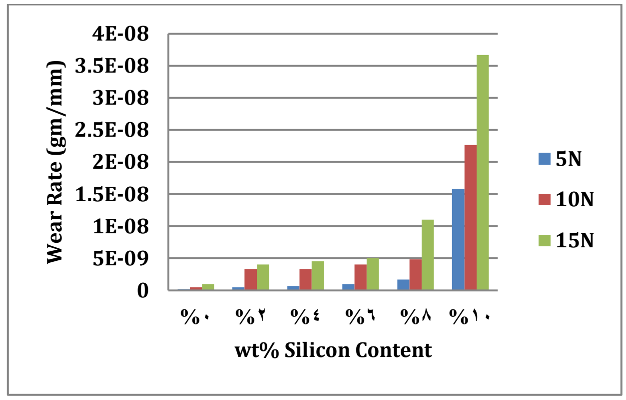


Figure 6. Wear rates at loads of (5N, 10N and 15N).

3.5 Compression Strength

From the compression stress-strain curve, the mechanical properties of the samples (i.e., yield strength, ultimate compressive strength and elastic modulus) were derived. Briefly, the yield strength is the stress at which the material begins to deform plastically, whereas the ultimate compressive strength was defined as the maximum stress before fracture and finally the elastic modulus was calculated from the slope of elastic response of the samples before yielding.
From **Figure (7)**, the yield strength decreases with increasing Silicon content as the percentage of porosity increases with the Silicon content, and this is also true in the case of ultimate compressive strength which is represented in **figure (8)**. Moreover, the elastic modulus is decreasing continuously from (21.92 GPa) for (CP-Ti) to (4.88 GPa) for (Ti-Si) alloy sample with (10 wt%) Silicon, this continuous decrement in elastic modulus is obviously related to the increase in porosity which is directly related to the silicon content, as shown in **figure (9).**
From the results, the compressive strength, yielding strength and Young's modulus strongly depended on the porosity and pore size, and adversely related to the porosity percentage and this agreed with the previous work **[7]**. It was found that only the yield strengths and the compressive strengths of (Ti-Si) alloys containing (4, 6 and 8 wt%) Silicon were within the yield strength values of natural bone (130-180 MPa) and ultimate compressive strengths that reported for human cortical bone (140–220 MPa) , and

finally all the values of elastic modulus belongs to the studied samples were within the elastic modulus values of natural bone (4-30 GPa). The mechanical properties results indicate the suitability of the samples for implant applications since they are not only able to minimize the stress-shielding effect but they also show suitable yield strengths for the implant material to resist against permanent shape change under loading.

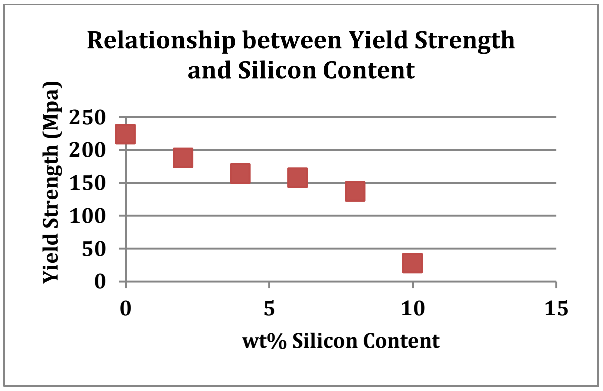


Figure 7. Yield strengths at different Silicon contents.

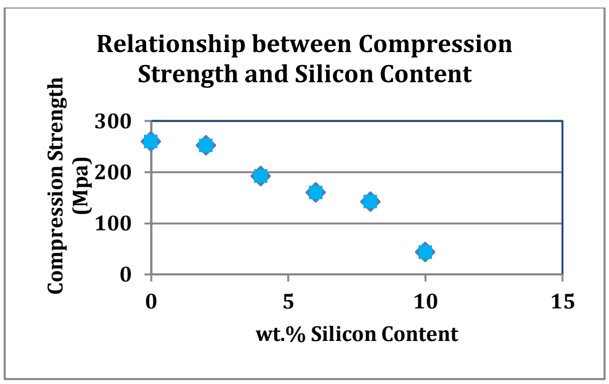


Figure 8. The ultimate compression strengths at different Silicon contents.

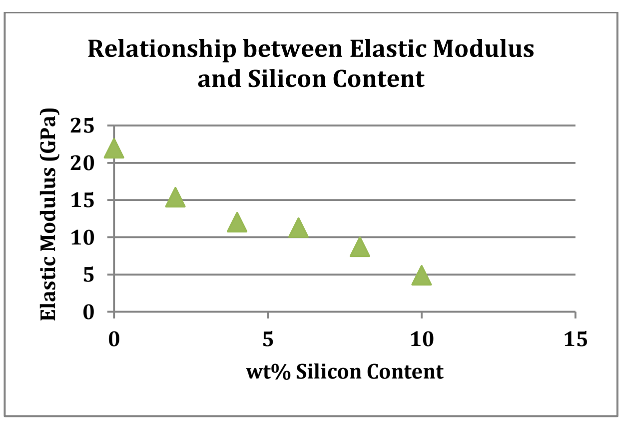


Figure 9. elastic moduli at different Silicon contents.

4. Conclusions

The following points were concluded:

(1) The XRD patterns of the samples with Silicon content of (0 and 2 wt%) comprise of single phase (α-phase), with increasing the Silicon content to (4, 6, 8 and 10 wt%) the alloy comprises of (α-phase) and (Ti_5Si_3) intermetallic compound.

(2) For all the (Ti-Si) alloys, all the (XRD) peaks are shifted to lower angles with the increase in Silicon content.

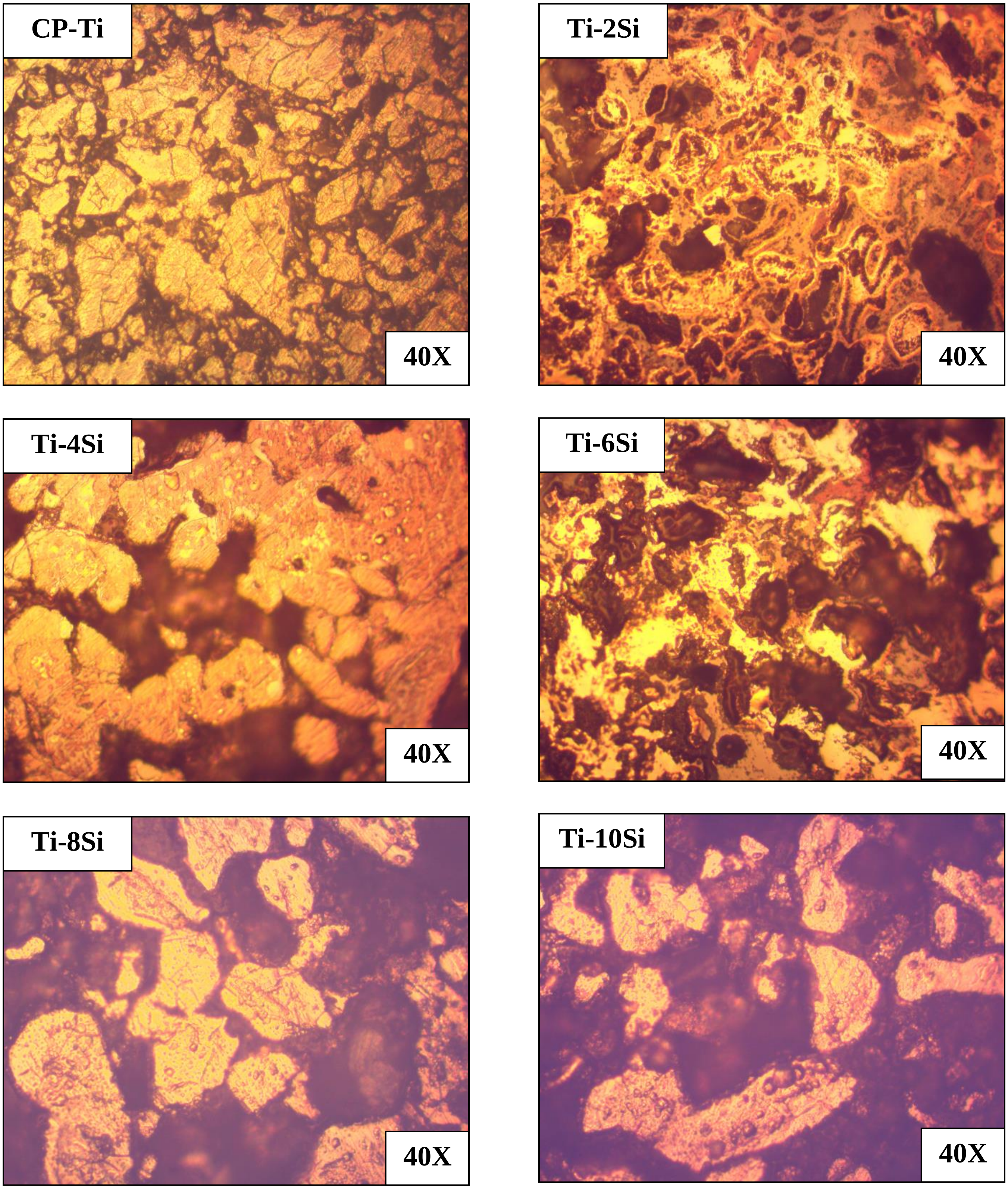
(3) The porosity percentage increase with the increase in Silicon content.

(4) The hardness decreases with the increase in Silicon content due to the increase in porosity percentage. There is no significant effect for Ti_5Si_3 intermetallic compound on improving the hardness of the samples and this is attributed to its low percent and the major effect of porosity on hardness which declined the Ti_5Si_3 effect by reducing the hardness of the (Ti-Si) alloys compared with the (CP-Ti) sample.

(5) The wear rate increases with the increase in Silicon content due to the increase in porosity percentage.

(6) The obtained results of mechanical properties (yield strength, ultimate compressive strength and Young's modulus) were within the values that match bone's properties.

Appendix



Optical microstructure images of the (CP-Ti) and (Ti–Si) alloys samples.

References

[1] C. Veiga, J. Davim and A. Loureiro, "Properties and applications of titanium alloys: a brief review" in Journal Reviews on Advanced Materials Science, 2012; 32: 14-34.
[2] Z. Hu, Y. Zhan and J. She, "The role of Nd on the microstructural evolution and compressive behavior of Ti–Si alloys," in Journal of Materials Science and Engineering, 2013; 560: 583–588.
[3] Y. Chen, J. Frith, A. Manshadi, H. Attar, D. Kent, N. Soro and M. Dargusch, "Mechanical properties and biocompatibility of porous titanium scaffolds for bone tissue engineering," in Journal of the Mechanical Behavior of Biomedical Materials, 2017; 75: 169–174.
[4] M. Khodaei, M. Meratian, O. Savabi and M. Razavi, "The effect of pore structure on the mechanical properties of titanium scaffolds," in journal of Materials Letters, 2016; 171: 308–311.
[5] J. Oh, J. Lim, B. Lee, C. Suh, S. Cho, S. Lee, and G. Choi, "Grain Refinement and Hardness Increase of Titanium via Trace Element Addition," in journal of Materials Transactions, 2010; 51: 2009–2012.
[6] I. Kopova, J. Strasky, P. Harcubab, M. Landac, M. Janecekb, L. Bacakova, "Newly developed Ti–Nb–Zr–Ta–Si–Fe biomedical beta titanium alloys with increased strength and enhanced biocompatibility," in journal of Materials Science and Engineering: C, 2016; 60: 230–238.
[7] B. Dabrowski, J. Kaminski, W. Swieszkowski and K. Kurzydlowski, "Porous Titanium Scaffolds for Biomedical Applications: Corrosion Resistance and Structure Investigation," in journal of Materials Science Forum, 2011; 674: 41-46.